



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**EFFECT OF THE ENVIRONMENT AND
ENVIRONMENTAL UNCERTAINTY ON SHIP ROUTES**

by

Stacey L. Hall

June 2012

Thesis Advisor:

Thesis Co-Advisor:

Second Reader:

Eva Regnier

Jim Hansen

Dashi Singham

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2012	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE Effect of the Environment and Environmental Uncertainty on Ship Routes			5. FUNDING NUMBERS	
6. AUTHOR(S) Stacey L. Hall				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) The United States Navy (USN) uses Optimal Track Ship Routing provided by ship routing officers (SRO) to aid in the safe transit of its ships. When a ship makes a transit, the ship provides the SRO an origin, a destination, and a date of departure, and the SRO will generate a route for the ship to proceed along. Avoiding severe weather is the most important consideration in determining the route. In addition to safe transit, the USN also focuses on fuel efficiency. In recent years, the meteorology and oceanography community has been providing more products that estimate the uncertainty in environmental forecasts. However, it is not known how much that uncertainty affects or should affect ship routing. This thesis explores the sensitivity and robustness of optimized ship routes generated by the Ship Track and Routing System optimizer to uncertainty in the environment.				
14. SUBJECT TERMS Automated Optimum Track Ship Routing, Environmental Forecast, Robustness, Sensitivity			15. NUMBER OF PAGES 89	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

**EFFECT OF THE ENVIRONMENT AND ENVIRONMENTAL UNCERTAINTY
ON SHIP ROUTES**

Stacey L. Hall
Lieutenant, United States Navy
B.A., The University of Southern Mississippi, 2003

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

**NAVAL POSTGRADUATE SCHOOL
June 2012**

Author: Stacey L. Hall

Approved by: Eva Regnier
Thesis Advisor

Jim Hansen
Thesis Co-Advisor

Dashi Singham
Second Reader

Robert Dell
Chair, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The United States Navy (USN) uses Optimal Track Ship Routing provided by ship routing officers (SRO) to aid in the safe transit of its ships. When a ship makes a transit, the ship provides the SRO an origin, a destination, and a date of departure, and the SRO will generate a route for the ship to proceed along. Avoiding severe weather is the most important consideration in determining the route. In addition to safe transit, the USN also focuses on fuel efficiency. In recent years, the meteorology and oceanography community has been providing more products that estimate the uncertainty in environmental forecasts. However, it is not known how much that uncertainty affects or should affect ship routing. This thesis explores the sensitivity and robustness of optimized ship routes generated by the Ship Track and Routing System optimizer to uncertainty in the environment.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	BACKGROUND	1
B.	RESEARCH QUESTIONS.....	3
C.	LITERATURE REVIEW	4
D.	SCOPE OF THESIS	5
II.	DESIGN OF EXPERIMENTS	7
A.	SIMULATION ENVIRONMENT	7
1.	METOC Environments	7
2.	STARS Input	8
3.	STARS Output	10
B.	EXPERIMENTAL ROUTES	12
III.	ANALYSIS AND RESULTS	19
A.	OVERVIEW.....	19
B.	PERFORMANCE ANALYSIS AND RESULTS.....	19
C.	MEASURING SENSITIVITY.....	22
D.	MEASURING ROBUSTNESS	43
IV.	CONCLUSIONS	55
A.	SUMMARY	55
B.	FUTURE WORK RECOMMENDATIONS	55
APPENDIX A.	SAMPLE OF STARS INPUT FILE.....	57
APPENDIX B.	SAMPLE OF STARS EXECUTIBLE FILE.....	59
APPENDIX C.	SAMPLE OF STARS HYPERTEXT MARKUP LANGUAGE OUTPUT FILE	61
	LIST OF REFERENCES.....	67
	INITIAL DISTRIBUTION LIST	69

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1.	UBs and LBs Envelope for a Route Between San Francisco, CA and Pearl Harbor, HI (From Google Earth, 2010)	9
Figure 2.	UBs and LBs Envelope for a Route Between Capetown, South Africa and Hobart, Australia (From Google Earth, 2010)	9
Figure 3.	Norfolk, VA to Rota, Spain (06012010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011)	15
Figure 4.	Pearl Harbor, HI, to Yokosuka, Japan (06022010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011).....	15
Figure 5.	San Diego, CA, to Naval Station Guam (06032010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011).....	16
Figure 6.	Pearl Harbor, HI, to Yokosuka, Japan (08162010), Shows how Environments can be so Similar that the Same Route is Generated for Nearly all of the Environments (From Google Earth, 2011)	16
Figure 7.	Seventeen Different Routes Generated by STARS for the Origin-destination Pair of Norfolk, VA, to Rota, Spain (12012010) (From Google Earth, 2011).....	17
Figure 8.	Optimized Routes Generated for Norfolk-Rota Route, 08012010 (From Google Earth, 2011).....	27
Figure 9.	Optimized Routes Generated for Norfolk-Rota Route, 10012010 (From Google Earth, 2011).....	28
Figure 10.	Optimized Routes Generated for Norfolk-Rota Route, 12012010 (From Google Earth, 2011).....	29
Figure 11.	Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 06162010 (From Google Earth, 2011).....	33
Figure 12.	Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 07162010 (From Google Earth, 2011).....	34
Figure 13.	Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 12162010 (From Google Earth, 2011).....	35
Figure 14.	Optimized Routes Generated for San Diego-Guam Route, 08032010 (From Google Earth, 2011).....	39
Figure 15.	Optimized Routes Generated for San Diego-Guam Route, 09032010 (From Google Earth, 2011).....	40
Figure 16.	Optimized Routes Generated for San Diego-Guam Route, 10032010 (From Google Earth, 2011).....	41
Figure 17.	Optimized Routes Generated for San Diego-Guam Route, 10032010 (From Google Earth, 2011).....	42

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Notation and Definitions for Geographical Locations.....	10
Table 2.	Notation and Definitions for Ship's Course, Speed and Distance	10
Table 3.	Notations and Definitions of STARS Outputs.....	11
Table 4.	Departure and Arrival Dates for the Routes Between Norfolk, VA and Rota, Spain.....	13
Table 5.	Departure and Arrival Dates for the Routes Between Pearl Harbor, HI and Yokosuka, Japan	14
Table 6.	Departure and Arrival Dates for the Routes Between San Diego, CA and Naval Station Guam.....	14
Table 7.	For Each Departure Date for the Norfolk-Rota Route, Total Horsepower and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route.....	20
Table 8.	For Each Departure Date for the Pearl Harbor-Yokosuka Route, Total Energy Consumption and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route.....	21
Table 9.	For Each Departure Date for the San Diego-Guam Route, Total Energy Consumption and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route	22
Table 10.	For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From Reference Routes (Summary Statistics Over Routes Optimized for Each Ensemble Member).....	24
Table 11.	For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	25
Table 12.	For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From the Averaged Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	26
Table 13.	For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Average of all Ensemble Members and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route.....	30
Table 14.	For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	31

Table 15.	For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Averaged Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	32
Table 16.	For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average of all Ensemble Members and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	36
Table 17.	For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average of the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	37
Table 18.	For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route	38
Table 19.	Robustness of the Optimized Routes for Norfolk to Rota	45
Table 20.	Robustness of the Optimized Routes for Pearl Harbor to Yokosuka.....	46
Table 21.	Robustness of the Optimized Routes for San Diego to Guam.....	47
Table 22.	Optimized Routes for Norfolk to Rota Under Actual METOC Conditions	48
Table 23.	Optimized Routes for Pearl Harbor to Yokosuka Under Actual METOC Conditions	49
Table 24.	Optimized Routes for San Diego to Guam Under Actual METOC Conditions	49
Table 25.	Overall Mean and Maximum Safety Experiences Along Norfolk to Rota Routes	50
Table 26.	Overall Mean and Maximum Safety Experiences Along Pearl Harbor to Yokosuka Routes	51
Table 27.	Overall Mean and Maximum Safety Experiences along San Diego to Guam Routes.....	52

LIST OF ACRONYMS AND ABBREVIATIONS

AOTSR	Automated Optimum Track Ship Routing
BBLS	Barrels
CVN	Nuclear Powered Aircraft Carrier
DFM	Distillate Marine Fuel
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GC	Great-Circle
HTML	HyperText Markup Language
KHPH	Kilo-Horsepower-Hours
LB	Lower Bound
METOC	Meteorological and Oceanography
NCOM	Navy Coastal Ocean Model
NM	Nautical Miles
NOGAPS	Navy Operational Global Atmospheric Prediction System
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
NWS	National Weather Service
OTSR	Optimal Track Ship Routing
POL	Petroleum, Oil and Lubricant
SOE	Safe Operating Envelopes
SRO	Ship Routing Officer
STARS	Ship Tracking and Routing System
UB	Upper Bound
USDoN	United States Department of the Navy
USN	United States Navy
WWIII	Wavewatch III

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Meteorology and oceanography (METOC) forecasters rely heavily on numerical models. Numerical weather prediction (NWP) models are discretized mathematical models consisting of basic differential equations simulating the fluid dynamic process and physics of the environment. Based on Newton's second law of motion, basic equations are solved for any point (location and altitude) at any given time in the atmosphere for dependent variables that describe the atmosphere and stepped through time to obtain predictions of the future behavior of the atmosphere. Depending on the horizontal and vertical spacing of the discretization, some aspects of the equations are solved explicitly while smaller-scale operations are "parameterized." Solutions to all equations for each point are coupled with neighboring points, and all equations with their solutions are stepped forward in time simultaneously until the desired forecast length is achieved.

Ensembles are a way of using numerical models to quantify uncertainty in environmental conditions. An ensemble forecast can be generated from the use of two or more different forecast techniques or numerical models, or using multiple numerical models with different initial conditions.

NWP forecasts are driven primarily by initial conditions. Initial conditions are the model's variable values at $t = t_0$, where t represents time, from which the model's forecast is stepped forward. The initial estimates of the model variables are more important than the model boundary conditions. The initial value of every variable at every location in the model must be specified. Since observations are not available in all locations and because the available observations often differ from the variables solved by the NWP model, initial conditions are uncertain. To account for this uncertainty, ensemble forecasting runs the model several times. Each time the model is run, the initial conditions are perturbed slightly. Small changes in initial conditions can lead to large differences in forecast values, and the collection of ensemble forecasts provides an estimate of the expected error in the forecast.

This thesis explores the sensitivity and robustness of optimized ship routes generated by the Ship Track and Routing System (STARS) optimizer to uncertainty in the environment. Environmental uncertainty is represented by an ensemble generated from numerical weather models. STARS uses the Naval Operational Global Atmospheric Prediction System (NOGAPS) for the wind model. The Wavewatch III (WWIII) model is used as the wave model, and the global Navy Coastal Ocean Model (NCOM) is used as the current model.

This thesis sets out to answer questions regarding the sensitivity and robustness of ship routes to environmental conditions and how important it is to take into consideration environmental uncertainty when determining a robust ship route. The sensitivity of the optimized routes showed that there were few routes that differed greatly in distance varying environmental forecasted conditions. The robustness of the optimized routes showed that the routes were safe under various environmental conditions. The time of year, with respect to seasons, is a major factor in the uncertainty of environmental conditions. The time of year and the forecasted weather conditions should definitely be taken into consideration when trying to determine a robust ship route.

Given that weather is a variable that cannot be controlled, it is important to understand how that uncertainty can affect a ship route. The optimized routes that were generated by STARS showed little sensitivity and were robust to the environmental conditions. Although the environmental conditions proved to have an impact on the optimized routes, the generated routes were, for the most part, the best and the safest route to take. However, because forecasted weather is not a guarantee but an estimate of a possible occurrence, ship routes based on forecasted environmental conditions are subject to change with the changing conditions. The optimized routes can be used as a basis, but it should be clear that even an optimized route may need to be altered to maintain robustness.

ACKNOWLEDGMENTS

I owe the greatest debt of gratitude to my parents, Charles and Hazel Hall, for their unconditional love and support. They were there for me during this entire process, as they have been throughout every aspect of my life. Their words of encouragement were always just what I needed to keep me going, even when I felt that I could go no further. I also owe a debt of gratitude to the members of Saint Peter United Methodist Church in Meridian, Mississippi. They are my extended family, and they have supported me in all of my endeavors.

There are many faculty and staff members of the Operations Research department at NPS who were immensely supportive, but many deserve special recognition and thanks. My advisor, Associate Professor Eva Regnier, whose diligence and patience were instrumental in the completion of this thesis. CAPT Jeffrey Kline, USN (ret.), CAPT Carol O'Neal, USN (ret.), CDR Kevin Maher, USN (ret.) and CDR David Schiffman were well aware of the difficulty I experienced while at NPS, and they were always there to give their vote of confidence in my ability to complete my degree and thesis.

I extend special thanks to Dr. Jim Hansen and the Naval Research Laboratory in Monterey, California. Dr. Hansen was a wonderful co-advisor. His familiarity and knowledge of the STARS software was necessary for my success. I am thankful to the faculty and staff of the Naval Research Laboratory for allowing me to conduct my experimental runs and simulations at their facility.

Special thanks are extended to my life-long friends that I met along my journey: Chante Davis, LCDR Edwaun Durkins, USN, and MAJ Farrah Thompson, USMC, for their concern, confidence, support and time during my difficult journey.

To my thesis editor, Steven Cyncewicz, I definitely couldn't have done this without him. His patience, support, and expertise were greatly appreciated in putting this thesis together.

My final thanks are given to the businesses and organizations in the Monterey area that made my time enjoyable. To the pastors and members of the Community Missionary Baptist Church, thank you for your continued prayers and support. To the staff of the Monterey County Rape Crisis Center, thank you for giving me the opportunity to continue my passion in sexual-assault education and prevention and for giving me the opportunity to share my strength to those in need. Last, but certainly not least, thanks to the owner and staff of the Sardine Factory for always providing a relaxing atmosphere when I needed a mini-vacation.

I. INTRODUCTION

A. BACKGROUND

The mission of the United States Navy (USN) is to provide a naval force capable of ensuring that the freedom of the seas is maintained for the United States and its allies. Moored pier side or underway, ships are vulnerable to the environmental conditions that they encounter. A simple transit across the Atlantic Ocean can easily become a rough voyage if the ship encounters high winds, which in turn will cause a high sea state.

Environmental conditions play a crucial role in safe navigation. Each USN ship class has a set of safe operating envelopes (SOE). These SOE indicate the maximum seas and the maximum winds in which the ship can safely operate. If conditions that exceed the SOE are not avoided, the ship is at risk to receive extensive damage or even be a total loss; there is also a risk of injury to or loss of ship crew members.

History has shown that extreme environmental conditions can cause damage to a ship and the crew that it holds. The Naval Historical Center lists approximately forty weather-related incidents in naval history from 1781 to 1949, most of which were caused by gale force winds, heavy squalls, hurricanes, storms, and typhoons (Naval Historical Center, 2005). In December 1944, the ships of Task Force 38 were overwhelmed by a typhoon that claimed three destroyers and the lives of approximately 790 officers and men; the typhoon also caused severe damage to a cruiser, five aircraft carriers and their planes, and three other destroyers, and injured over eighty personnel (Naval Historical Center, 2001). More recently, in November 2005 while returning home from a UNITAS deployment, the USS Ross (DDG51) was hit by rough seas, causing a crack in the hull and damaging the ship's sonar equipment rooms (A. Corbin, personal communication, April 13, 2011). In each of these incidents, the effects of the unexpected environmental conditions encountered proved costly.

The USN uses Optimal Track Ship Routing (OTSR) provided by ship routing officers to aid in the safe transit of its ships. Typically, ship routing officers (SRO) monitor as many as 5,300 routes a year (F. Sullivan, personal communication, April 15,

2011). Prior to departure, a ship provides the SRO an origin, a destination, and a date of departure, and the SRO will generate a route for the ship to proceed along that is forecasted to be consistent with the ship's operational limits. However, the route is subject to change.

There are many reasons for a ship to change its route, but the most typical weather-related reason to alter the route is to avoid or minimize its exposure to sea and wind conditions which exceed the ship's SOE. Even though the ship receives weather advisories, there are some cases in which the advisories are not sent to or received by the ship in time to prepare for the change in the weather. Uncertainties in weather play a vital role in the safe navigation of the ship. The SRO provides an alternative route to modify a ship's route due to hazardous weather or tropical cyclone avoidance. If a USN ship chooses to be non-compliant with the OTSR diversion recommendations, they must receive permission from the respective Fleet Commander via the ship's respective fleet number. This situation usually occurs when the mission is of great importance.

A second important consideration in ship routing is fuel. The Ticonderoga-class (CG47) cruiser has the capacity to hold over 15,000 barrels (bbls) of distillate marine fuel (DFM) (United States Department of the Navy [USDoN], 2007). As stated in USDoN (2007), the petroleum, oil and lubricant (POL) requirement for the CG47 class is over 750 bbls per day for sustainment at sea. This is an average POL fuel consumption rate, but there are other factors that influence fuel consumption. Fuel consumption is affected by speed traveled, distance traveled, and the environmental conditions experienced along the route. When considering factors that influence fuel consumption, the intensity and direction of both waves and winds are primary (Brown, Kline, Rosenthal & Washburn, 2007).

Meteorology and oceanography (METOC) forecasters rely heavily on numerical models. Numerical weather prediction (NWP) models are discretized mathematical models consisting of basic differential equations simulating the fluid dynamic process and physics of the environment. Based on Newton's second law of motion, basic equations are solved for any point (location and altitude) at any given time in the atmosphere for dependent variables that describe the atmosphere and stepped through

time to obtain predictions of the future behavior of the atmosphere (Lynch, 2008). Depending on the horizontal and vertical spacing of the discretization, some aspects of the equations are solved explicitly while smaller-scale operations are “parameterized.” Solutions to all equations for each point are coupled with neighboring points, and all equations with their solutions are stepped forward in time simultaneously until the desired forecast length is achieved.

Ensembles are a way of using numerical models to quantify uncertainty in environmental conditions. Sivillo, Ahlquist, and Toth (1997) define an ensemble forecast as “a collection of two or more forecasts that verify at the same time.” An ensemble forecast can be generated from the use of two or more different forecast techniques or numerical models, or using multiple numerical models with different initial conditions.

NWP forecasts are driven primarily by initial conditions. Initial conditions are the model’s variable values at $t = t_0$, where t represents time, from which the model’s forecast is stepped forward. The initial estimate of the model variables is more important than the model boundary conditions. The initial value of every variable at every location in the model must be specified. Since observations are not available in all locations and because the available observations often differ from the variables solved by the NWP model, initial conditions are uncertain. To account for this uncertainty, ensemble forecasting runs the model several times. Each time the model is run, the initial conditions are perturbed slightly. Small changes in initial conditions can lead to large differences in forecast values, and the collection of ensemble forecasts provides an estimate of the expected error in the forecast.

B. RESEARCH QUESTIONS

An important question for the METOC community is how much METOC forecasts affect ship routes and how severe are the consequences of following a non-optimal route. Therefore, this thesis addresses the following questions:

1. How sensitive are optimal ship routes to environmental conditions, i.e., waves and wind as predicted by distinct forecasts?

2. How robust is the optimized ship route to the variability of environmental conditions as represented by multiple distinct forecasts for the same time period?
3. How valuable is taking environmental uncertainty into account when finding a robust ship route?

C. LITERATURE REVIEW

There has been little research done on the effect of uncertainty in environmental conditions on naval operations. Stoughton (2010) focuses on the wind thresholds as they apply to a USN nuclear powered aircraft carrier (CVN) during ammunition offload. Stoughton uses an ensemble to generate a probabilistic forecast and bases a routing decision on that forecast. In this thesis, each ensemble member is treated as a separate deterministic forecast and an optimal route is found with respect to each of those forecasts.

Other authors have addressed optimizing ship routes with respect to the environment. Montes (2005) uses shortest path models to analyze ship routing and provide an operations research tool to aid in the initial route planning, recommendation, and diversions. Montes shows that the use of OTSR is a useful tool to analyze parameter sensitivities when planning route diversions. Vlachos (2004) proposes two methods for generating nearly optimal ship routes, using transit time and safety (a function of seas and winds) as the objective. Vlachos treats the environment as deterministic. Dolinskaya, Kotinis, Parsons, and Smith (2009) investigate the involuntary loss of speed caused by added resistance and the limitations imposed on the vessel by operational constraints. The results of the seakeeping model provide the maximum attainable speed for a given sea state and ship heading.

D. SCOPE OF THESIS

This thesis explores the sensitivity and robustness of optimized ship routes generated by the Ship Track and Routing System (STARS) optimizer to uncertainty in the environment. Environmental uncertainty is represented by an ensemble generated from numerical weather models. STARS uses the Naval Operational Global Atmospheric Prediction System (NOGAPS) for the wind model. The Wavewatch III (WWIII) model is used as the wave model, and the global Navy Coastal Ocean Model (NCOM) is used as the current model.

THIS PAGE INTENTIONALLY LEFT BLANK

II. DESIGN OF EXPERIMENTS

Using optimization code provided by the Naval Research Laboratory (NRL) with STARS, “optimal” ship routes were generated for multiple forecast environments for three frequently traveled origin-destination pairs from June 2010 to December 2010. These ship routes were generated to explore the sensitivity and robustness of optimal routes to uncertain environmental conditions as modeled with ensemble wind, wave, and current forecasts.

A. SIMULATION ENVIRONMENT

STARS was developed by Oceans System Incorporated in Alameda, California. It is a software package that generates optimal ship routes based on weather model data (Montes, 2005). It takes as an input forecast METOC conditions and produces a route that minimizes total energy required for propulsion subject to constraints on METOC environmental conditions for a given forecast environment (J. Etro, personal communication, May 13, 2011). Appendix A contains a sample of a STARS input file, which shows the environmental constraints applied to the generated routes. These constraints are 35 knots of wind speed, 65 knots of relative wind speed, and 25-foot seas. The STARS program uses the DD963 Spruance-class destroyer as its modeled platform. Although this class of ship has been decommissioned, its characteristics have been maintained in today’s Ticonderoga-class cruiser. When STARS was presented to the USN, it was part of the Automated Optimum Track Ship Routing (AOTSR) system, a system used by SRO to assist them in OTSR. However, ship routers were reluctant to use this software because it was designed for merchant vessels and was difficult to use (Montes, 2005).

1. METOC Environments

The environments in STARS used in this thesis are the members of a sixteen-member ensemble generated from the NOGAPS model for winds, WWIII model for waves, and NCOM for currents. The initial conditions for the sixteen environments are generated by perturbing the most recent analysis using an ensemble transform analysis

perturbation scheme (McLay, Bishop, & Reynolds, 2010). Hogan, Rosmond, and Gelaro (1991) give a detailed description of the NOGAPS model. The NOGAPS model is crucial to nearly every environmental product produced by the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and it is the foundation of the Navy's operational and environmental central site fleet support. In STARS, WWIII is an offline model. It can receive any wind field forecast, which is then used to determine waves. The wind fields are generated in the NOGAPS model and passed to the WWIII model. The global NCOM provides surface boundary conditions, which in turn are provided by the NOGAPS (National Weather Service [NWS], 2009). NCOM uses moisture and heat from the lower atmosphere to generate currents and receives atmospheric forces from the NOGAPS (J. Hansen, personal communication, May 16, 2011). The WWIII waves and NCOM currents are generated for each NOGAPS environment, providing a forecast environment that includes winds, waves, and currents for each of the sixteen environments.

The environments are arbitrarily named and indexed $i = 1, \dots, M, M = 16$. All are generated the same way. There are two other environment options available in STARS. The “analysis” is the best estimate of the environmental; it is also the time zero forecast for the numerical model. The “ensembleaverage” environment is the average value of all the selected raw ensemble members (J. Hansen, personal communication, May 12, 2011).

2. STARS Input

STARS optimizes on a grid that is contained within a user-defined envelope. For each route, the input file specifies the upper bounds (UBs) and lower bounds (LBs) of the envelope, each represented in the form of a latitude-longitude pair to the tenth of a degree. UB NUMBER 01 and LB NUMBER 01 are the same latitude-longitude pair, which is the route origin, while UB NUMBER 04 and LB NUMBER 04 are the same and represent the route destination. In addition, STARS requires two UBs and two LBs that create the envelope. The envelope should resemble the shape of a football and it should not include any land masses. The envelope for each origin-destination pair was chosen manually. The UBs and LBs chosen were far away from the expected route as possible

so as to not constrain the optimized route. Figures 1 and 2 illustrate the envelope made by the UBs and LBs. Figure 1 is in open ocean, and Figure 2 shows how the envelope is adjusted to avoid land masses within the envelope.

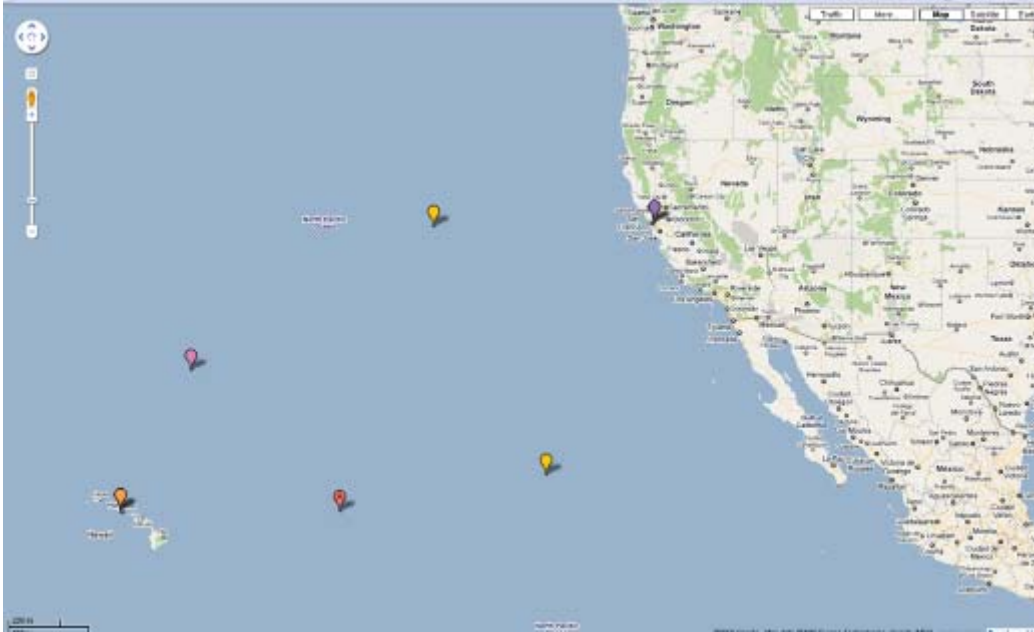


Figure 1. UBs and LBs Envelope for a Route Between San Francisco, CA and Pearl Harbor, HI (From Google Earth, 2010)



Figure 2. UBs and LBs Envelope for a Route Between Capetown, South Africa and Hobart, Australia (From Google Earth, 2010)

Appendix B contains an example of the executable file for STARS. The data in this file are used to run each simulation, and it is this file that points to the applicable input file. The departure date and arrival date are data input fields that are indicated by a dollar sign (\$) on the input file (Appendix A). The most important data for the execution file are the Routex environment and Weax environment data fields. Within the designated Routex environment, STARS takes the latitude-longitude pairs for the origin and destination, creates a grid-like diagram, and then optimizes the route for the given time of departure and arrival and the Routex environment.

3. STARS Output

Routes (denoted r) are uniquely determined by origin-destination pair, start date (arrival date is not a constraint), and Routex environment (indexed i). A route r consists of a set of N_r waypoints, $w_n, n = 1, \dots, N_r$, where the n^{th} waypoint is defined by the triplet $w_n = (d_n, x_n, y_n)$ (Table 1), where:

d_n	date-time group of n^{th} waypoint
x_n	latitude of n^{th} waypoint, -90.0° to 90.0° , where + indicates the Northern Hemisphere and – indicates the Southern Hemisphere.
y_n	longitude of n^{th} waypoint, 0.0° to 360.0°

Table 1. Notation and Definitions for Geographical Locations

The notation $w_n^*(i), x_n^*(i), y_n^*(i)$ will be used to denote the STARS-generated optimal route latitude and longitude for the n^{th} waypoint, optimized relative to environment i . The STARS output for an optimized route also includes the following (Table 2):

s_n	ship speed at n^{th} waypoint in knots
c_n	ship course at n^{th} waypoint, 0.0° to 360.0°
$dist_n$	distance in nautical miles (nm) to next waypoint

Table 2. Notation and Definitions for Ship's Course, Speed and Distance

Appendix C contains an example of a HyperText Markup Language (HTML) output file for STARS. Each row of this table corresponds to a waypoint, which are usually separated by six hours.

STARS also evaluates the route with respect to an environment—called the Weax environment—and indexed j that does not necessarily coincide with the Routex environment. STARS reports the following (Table 3):

$wind_speed(w_n, j)$	Surface wind speed in knots for the n^{th} waypoint evaluated with respect to environment j
$wind_direction(w_n, j)$	Surface wind direction, 0.0° to 360.0°
$sig_wave_height(w_n, j)$	Sea surface significant wave height in feet
$sea_height(w_n, j)$	Sea height in feet
$sea_period(w_n, j)$	Sea period in seconds
$sea_direction(w_n, j)$	Sea direction, 0.0° to 360.0°
$swell_height(w_n, j)$	Swell height in feet
$swell_period(w_n, j)$	Swell period in seconds
$swell_direction(w_n, j)$	Swell direction, 0.0° to 360.0°
$current_speed(w_n, j)$	Current speed in feet/second
$current_direction(w_n, j)$	Current direction, 0.0° to 360.0°
$horsepower(w_n, j)$	HP in kilo horsepower-hours since last waypoint

Table 3. Notations and Definitions of STARS Outputs

B. EXPERIMENTAL ROUTES

Preliminary simulations were conducted to see the behavior of STARS and its output data. One of the test simulations crossed the equator to verify the system was not confined to the Northern Hemisphere. Another test simulation only used three UBs and LBs instead of four to see if the number of bounds could be altered. Once an understanding of how certain inputs generated invalid outputs was reached, systematic simulations were started. Three routes that are frequently traveled by USN ships were chosen:

- Naval Station Norfolk, VA, to Naval Station Rota, Spain
- Naval Station Pearl Harbor, HI, to Naval Station Yokosuka, Japan
- Naval Station San Diego, CA, to Naval Station Guam

All routes were run using environments for the period June 2010 to December 2010. This period was chosen mostly due to the fact that environmental data were available starting in March 2010. Another reason for the selection of this timeframe was to have the opportunity to use environmental conditions over three of the four seasons: late summer, fall and winter. For each origin-destination pair two simulations were conducted each month, two weeks apart, with one simulation in the month of December for a total of thirteen simulations per origin-destination pair. The effect of an arrival date constraint was not explored in these experiments. The arrival date chosen for each origin-destination pair was the last day of the year, December 31, 2010. This arrival date was late enough that no simulation approached it; therefore, the arrival date did not constrain the routes.

Tables 4 to 6 show the origin-destination pairs and the departure dates and arrival dates of each simulation. Figures 3 to 7 show Google Earth images that depict the different routes that were generated for selected departure dates. STARS produces routes for each environment unless it cannot find a feasible route that does not exceed the SOE limitations in the input file within that environment. If STARS cannot find a route that does not exceed the SOE limitations, it does not produce a route. Given there are sixteen environments, STARS can produce between zero and sixteen different routes for a single origin-destination pair for a specified departure date. In some cases, two or more

environments will produce identical routes. Figures 3–7 show Google Earth images that include all of the routes generated by STARS for the entire set of origin-destination pairs for each route. Figures 6 and 7 show the differences in the number of routes generated by STARS for two specified departure dates. Given there are sixteen environments plus “analysis,” the route shown in Figure 6 only generated one route from the environments plus the “analysis” route, yielding a total of two routes. In Figure 7, for each environment plus the “analysis,” a different route was generated, yielding a total of seventeen routes.

Departure Date (MMDDYYYY)	Arrival Date (MMDDYYYY)
06012010	06082010
06152010	06222010
07012010	07082010
07152010	07222010
08012010	08082010
08152010	08222010
09012010	09082010
09152010	09222010
10012010	10082010
10152010	10222010
11012010	11082010
11152010	11222010
12012010	12082010

Table 4. Departure and Arrival Dates for the Routes Between Norfolk, VA and Rota, Spain

Departure Date (MMDDYYYY)	Arrival Date (MMDDYYYY)
06022010	06102010
06162010	06242010
07022010	07102010
07162010	07242010
08022010	08102010
08162010	08242010
09022010	09102010
09162010	09242010
10022010	10102010
10162010	10242010
11022010	11102010
11162010	11242010
12022010	12102010

Table 5. Departure and Arrival Dates for the Routes Between Pearl Harbor, HI and Yokosuka, Japan

Departure Date (MMDDYYYY)	Arrival Date (MMDDYYYY)
06032010	06142010
06172010	06282010
07032010	07142010
07172010	07282010
08032010	08172010
08172010	08282010
09032010	09172010
09172010	09282010
10032010	10142010
10172010	10282010
11032010	11142010
11172010	11282010
12032010	12142010

Table 6. Departure and Arrival Dates for the Routes Between San Diego, CA and Naval Station Guam



Figure 3. Norfolk, VA to Rota, Spain (06012010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011)

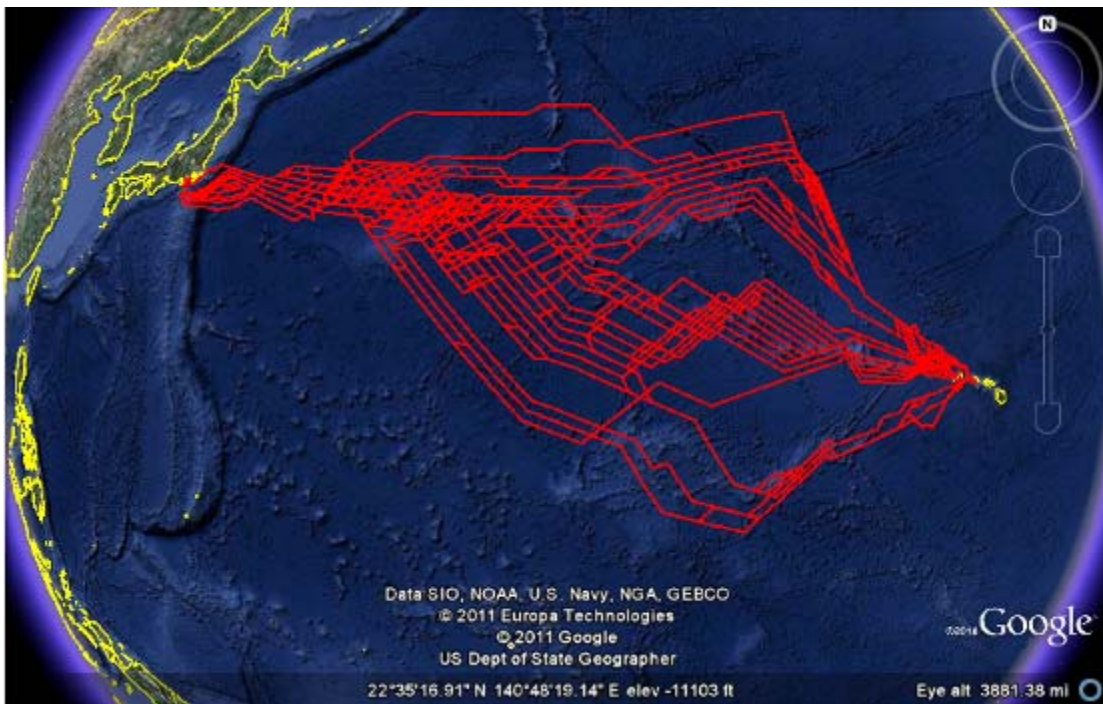


Figure 4. Pearl Harbor, HI, to Yokosuka, Japan (06022010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011)

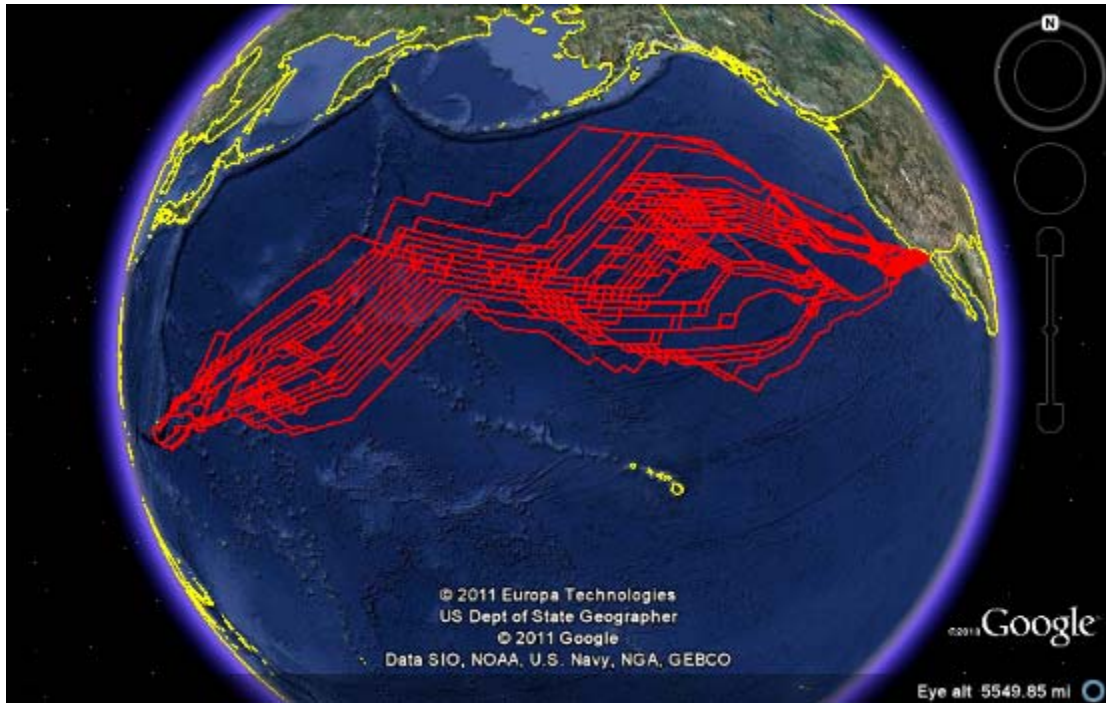


Figure 5. San Diego, CA, to Naval Station Guam (06032010), Showing STARS-generated Routes for Each Environment (From Google Earth, 2011)



Figure 6. Pearl Harbor, HI, to Yokosuka, Japan (08162010), Shows how Environments can be so Similar that the Same Route is Generated for Nearly all of the Environments (From Google Earth, 2011)



Figure 7. Seventeen Different Routes Generated by STARS for the Origin-destination Pair of Norfolk, VA, to Rota, Spain (12012010) (From Google Earth, 2011)

THIS PAGE INTENTIONALLY LEFT BLANK

III. ANALYSIS AND RESULTS

A. OVERVIEW

Every departure date for each origin-destination pair was analyzed to determine the performance, the sensitivity and the robustness of the routes generated. The performance of the routes is measured as the amount of energy consumed and the distance traveled. The sensitivity of the routes reflects how far apart optimized routes are, measured in terms of the distances among routes optimized with respect to different environmental forecasts. Robustness reflects how well the optimized route for a given origin-destination pair and start date stands up against the different environmental conditions, measured with respect to the safety of each route when environmental conditions are different from those used by the optimizer.

B. PERFORMANCE ANALYSIS AND RESULTS

The performance of the routes is measured as the amount of energy consumed and the distance traveled as an average of the indicated number of optimized routes generated for each specified departure date, as shown in Tables 7–9. As discussed earlier, STARS did not generate an optimized route for every environment. For each origin-destination pair and departure date, M' is the number of ensemble members for which an optimized route was generated. These performance tables show energy consumption (in kilowatt-hours, khph) and distance (in nautical miles, nm) along the optimized route with average and standard deviation over the M' ensemble members. The average time traveled was approximately the same for each specified origin-destination pair plus or minus an hour, regardless of the departure date. The Norfolk to Rota route took 179 hours. The Pearl Harbor to Yokosuka route took 189 hours, and the San Diego to Guam route took 270 hours.

For the Norfolk-Rota results, the average energy consumption and distances were similar during the earlier months. During the latter months, the energy consumption and distances increased, with the exception of 11012010. This reflects the generally more adverse environmental conditions during the later period, with the exception of 11012010, reflecting variability even within the fall season.

Origin-Destination	Departure Date (MMDDYYYY)	Total Energy Consumption (kWh) Average (StDev)	Total Distance (nm) Average (StDev)	Number of Optimized Routes Generated (M')
Norfolk - Rota	06012010	1853.3(10.2)	3719.2(5.2)	16
	06152010	1864.7(12.8)	3728.7(4.0)	16
	07012010	1823.0(9.0)	3720.8(3.4)	16
	07152010	1848.8(8.5)	3714.6(5.0)	16
	08012010	1810.2(11.6)	3714.3(1.9)	16
	08152010	1867.3(9.1)	3721.9(1.9)	16
	09012010	1826.5(7.0)	3720.8(2.7)	16
	09152010	1845.3(7.8)	3718.2(5.7)	16
	10012010	1944.0(19.1)	3735.0(1.6)	16
	10152010	1932.6(33.9)	3735.4(9.1)	16
	11012010	1890.9(29.2)	3722.6(4.8)	16
	11152010	1975.2(44.8)	3732.5(13.5)	16
	12012010	2197.1(93.9)	3747.6(27.2)	16
	12152010	2016.6(42.6)	3736.0(12.0)	14

Table 7. For Each Departure Date for the Norfolk-Rota Route, Total Horsepower and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route

For the Pearl Harbor-Yokosuka results, the average energy consumption is similar for most of the departure dates. The largest energy requirements were in November and December. The average total distance traveled showed small differences of no more than 50 nm over all departure dates.

Origin-Destination	Departure Date (MMDDYYYY)	Total Energy Consumption (kWh) Average (StDev)	Total Distance (nm) Average (StDev)	Number of Optimized Routes Generated (M)
Pearl Harbor - Yokosuka	06022010	2219.4(14.8)	4079.1(0.0)	16
	06162010	2320.0(37.5)	4091.2(0.1)	15
	07022010	2225.4(19.0)	4106.3(10.5)	15
	07162010	2194.6(23.1)	4087.5(5.2)	16
	08022010	2215.8(16.9)	4083.9(3.7)	15
	08162010	2216.1(16.3)	4068.7(0.5)	16
	09022010	2196.7(7.8)	4103.8(2.6)	16
	09162010	2250.1(9.2)	4102.8(6.5)	16
	10022010	2232.1(52.5)	4072.0(6.8)	16
	10162010	2258.2(44.4)	4071.0(6.7)	16
	11022010	2603.7(68.0)	4082.5(7.9)	15
	11162010	2522.4(66.5)	4082.9(14.1)	16
	12022010	2413.5(91.6)	4078.4(10.4)	16
	12162010	2360.8(62.0)	4056.9(7.2)	16

Table 8. For Each Departure Date for the Pearl Harbor-Yokosuka Route, Total Energy Consumption and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route

For the San Diego-Guam results, note that there are no results shown from departure date 12172010, presumably because adverse conditions prevented STARS from finding an optimal route that satisfied constraints. As with the other origin-destination pairs, the average energy consumption was greater during the winter months. The highest average energy consumption was experienced during December. The average total distances traveled varied by +/- 20 nm.

Origin-Destination	Departure Date (MMDDYYYY)	Total Energy Consumption (kph) Average (StDev)	Total Distance (nm) Average (StDev)	Number of Optimized Routes Generated (M')
San Diego - Guam	06032010	3670.4(66.7)	6065.4(0.0)	14
	06172010	3783.2(61.1)	6054.7(0.0)	15
	07032010	3772.3(50.1)	6059.7(0.0)	16
	07172010	3564.9(4.9)	6053.1(0.0)	14
	08032010	3560.5(14.7)	6056.5(6.4)	16
	08172010	3523.2(9.5)	6047.4(0.0)	15
	09032010	3652.3(22.4)	6068.4(3.4)	15
	09172010	3710.7(38.4)	6057.9(0.0)	16
	10032010	3742.6(34.5)	6081.7(14.5)	16
	10172010	3809.8(26.8)	6079.7(6.1)	16
	11032010	4073.7(219.9)	6044.4(0.0)	15
	11172010	3996.1(92.1)	6062.5(0.0)	16
	12032010	4126.0(88.8)	6047.8(0.0)	16
	12172010	NaN	NaN	NaN

Table 9. For Each Departure Date for the San Diego-Guam Route, Total Energy Consumption and Distance Traveled on Optimized Route, Averaged Over all Ensemble Members That Produced an Optimized Route

C. MEASURING SENSITIVITY

The sensitivity metrics reflect how much the routes generated from a given origin-destination pair and start date differ from each other. Tables 10–18 summarize how far apart the routes optimized with respect to the 16 ensemble members lie. Specifically, tables give the average (over M' ensemble members) of the average and the maximum (over the route) great-circle (GC) distance between each ensemble member's route and reference routes. The reference routes are:

- The average of the optimized routes from the 16 ensemble members (Tables 10, 13 and 16);
- The route optimized with respect to the analysis (11, 14, and 17); and

- The route optimized with respect to the average of the $M - 16$ ensemble-member environments (Tables 12, 15, and 18).

The distance between routes is measured in Tables 10–19 with both the average (Equation 1) and maximum over $N - 2$ waypoints, excluding the origin and destination of the GC distance between routes. The Routex environment used to optimize (i) is indicated in the row header, and j is the environment used to optimize reference route given in the column header.

$$\frac{1}{N-2} \sum_{n=2}^{N-1} \left(great_circle \left(x_n^*(i), y_n^*(i), x_n^*(j), y_n^*(j) \right) \right) \quad [1]$$

For Tables 10, 13, and 16, the results shown are averages (formula shown in Equation 2) and standard deviations over the number of ensemble members (M') for which STARS could generate an optimal route.

$$\frac{1}{M'} \sum_{i=1}^{M'} \left(\frac{1}{N-2} \sum_{n=2}^{N-1} \left(great_circle \left(x_n^*(i), y_n^*(i), x_n^*(j), y_n^*(j) \right) \right) \right) \quad [2]$$

Each table also shows the maximum GC distance between routes over the N waypoints, as in Equation 3 and, for Tables 10, 13, and 16, the average and standard deviation over all M' ensemble members are shown.

$$\max_n \left(great_circle \left(x_n^*(i), y_n^*(i), x_n^*(j), y_n^*(j) \right) \right) \quad [3]$$

Each origin-destination pair has departure dates with noteworthy results. Tables 10–12 show results for the Norfolk to Rota routes. Although the Norfolk to Rota routes show smallest maximal distances between routes, optimized routes for the same departure date may be more than 500 nm apart. Tables 10–12 show three departure dates for the Norfolk-Rota route that include an asterisk (*). Optimized routes for these departure dates, to include the analysis and the environment average routes, are shown in Figures 8–10.

There are four departure dates (07012010, 07152010, 11012010, and 12012010) for which the analysis-optimized route precisely coincides with the route optimized for the averaged-environments. Therefore, results for these two routes are the same and the distances between these two routes are zero.

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis- optimized Route	Averaged- Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Averaged- Environments- optimized Route	Average of Member- optimized Route
All Ensemble Members Average (StdDev)	06012010	50.8(18.2)	38.9(28.0)	34.5(11.2)	195.8(30.6)	227.3(69.1)	153.5(27.6)
	06152010	108.6(7.0)	12.4(17.0)	15.4(12.4)	332.6(33.0)	184.3(55.2)	165.1(42.7)
	07012010	41.9(16.2)	41.9(16.2)	33.9(7.7)	205.2(62.2)	205.2(62.2)	131.7(12.1)
	07152010	13.9(25.6)	13.9(25.6)	20.6(14.8)	121.9(45.8)	121.9(45.8)	99.8(26.5)
	08012010*	30.6(15.1)	8.4(13.9)	12.4(9.3)	239.9(75.2)	194.5(72.9)	158.2(47.6)
	08152010	24.2(19.6)	35.5(17.2)	23.8(11.3)	166.6(60.2)	189.2(46.3)	130.3(27.8)
	09012010	47.7(12.5)	28.4(27.6)	33.2(12.9)	227.2(44.0)	389.8(148.2)	290.7(78.5)
	09152010	49.7(19.2)	38.3(28.8)	34.0(21.9)	205.1(53.4)	270.2(69.6)	196.4(44.2)
	10012010*	26.7(21.0)	10.0(22.0)	14.9(17.9)	335.6(71.5)	335.6(82.3)	317.3(72.7)
	10152010	72.8(27.1)	59.4(20.5)	57.5(11.4)	360.2(74.4)	295.9(52.0)	243.0(39.4)
	11012010	41.7(44.4)	41.7(44.4)	47.3(35.0)	366.8(102.0)	366.8(102.0)	336.5(79.4)
	11152010	89.8(61.3)	107.2(49.8)	76.4(22.5)	463.7(152.0)	375.4(99.8)	295.8(53.8)
	12012010*	120.1(79.2)	120.1(79.2)	104.5(24.8)	503.9(187.1)	503.9(187.1)	380.6(79.8)
	12152010	85.3(57.9)	95.6(27.1)	75.1(15.8)	403.1(160.4)	316.0(79.8)	221.3(33.4)

Table 10. For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From Reference Routes (Summary Statistics Over Routes Optimized for Each Ensemble Member)

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis-optimized Route	Averaged Environments- optimized Route	Average of Member-optimized Route	Analysis-optimized Route	Averaged Environments- optimized Route	Average of Member-optimized Route
Analysis-Optimized Route	06012010	0	33.3	42.8	0	159.9	103.1
	06152010	0	109.6	107.2	0	310.7	297.1
	07012010	0	0	34.5	0	0	105.8
	07152010	0	0	13.5	0	0	24.4
	08012010*	0	35.7	30.4	0	194.5	158.2
	08152010	0	32.3	17.5	0	77.2	65.0
	09012010	0	41.2	34.5	0	227.2	128.7
	09152010	0	33.3	42.8	0	159.9	103.1
	10012010*	0	17.8	25.0	0	49.8	52.1
	10152010	0	73.2	54.4	0	235.5	154.1
	11012010	0	0	18.7	0	0	52.4
	11152010	0	157.2	80.4	0	359.3	186.3
	12012010*	0	0	93.7	0	0	175.2
	12152010	0	110.7	67.4	0	316.0	205.9

Table 11. For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis- optimized Route	Averaged Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Averaged Environments- optimized Route	Average of Member- optimized Route
Averaged Environments- Optimized Route	06012010	33.3	0	32.4	159.9	0	83.9
	06152010	109.6	0	8.6	310.7	0	22.9
	07012010	0	0	34.5	0	0	105.8
	07152010	0	0	13.5	0	0	24.4
	08012010*	35.7	0	6.7	194.5	0	36.3
	08152010	32.3	0	30.6	77.2	0	69.1
	09012010	41.2	0	23.3	227.2	0	101.2
	09152010	33.3	0	32.4	159.9	0	83.9
	10012010*	17.8	0	8.0	49.8	0	25.0
	10152010	73.2	0	36.1	235.5	0	91.4
	11012010	0	0	18.7	0	0	52.4
	11152010	157.2	0	89.5	359.3	0	213.6
	12012010*	0	0	93.7	0	0	175.2
	12152010	110.7	0	62.0	316.0	0	151.2

Table 12. For Each Departure Date for the Norfolk-Rota Route, Route Average GC Distance and Maximum GC Distance From the Averaged Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route



Figure 8. Optimized Routes Generated for Norfolk-Rota Route, 08012010 (From Google Earth, 2011)



Figure 9. Optimized Routes Generated for Norfolk-Rota Route, 10012010 (From Google Earth, 2011)

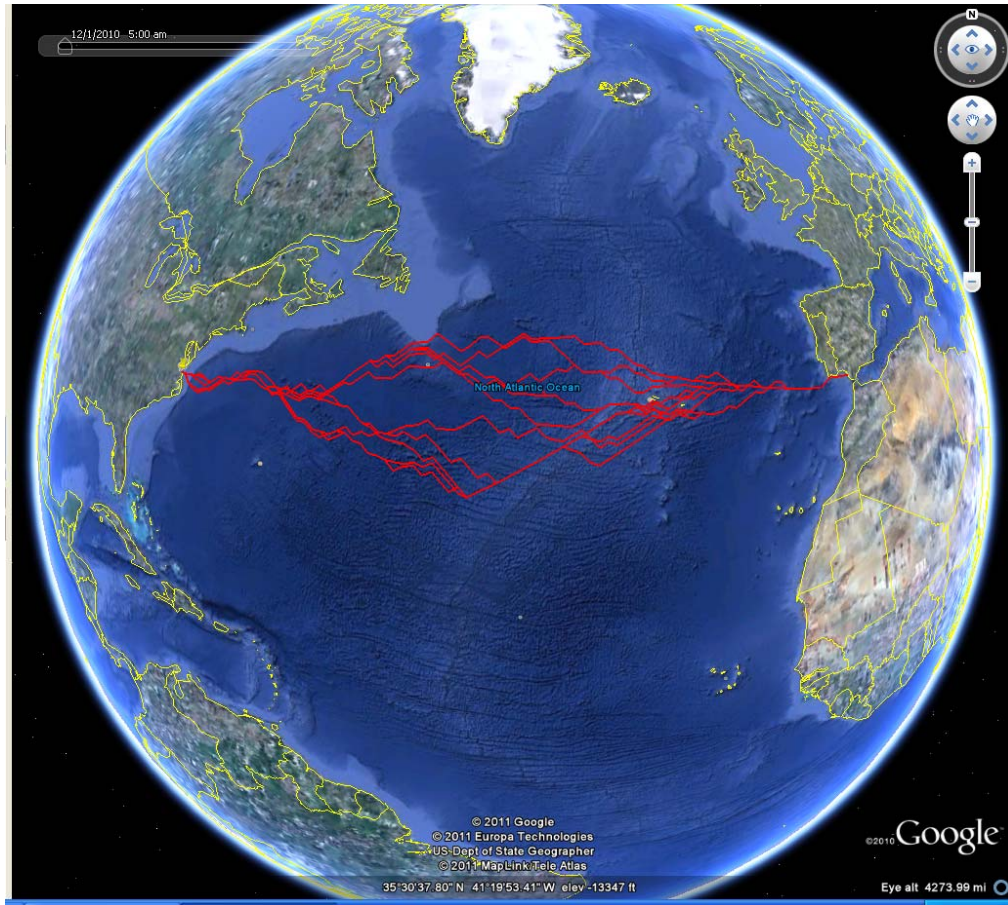


Figure 10. Optimized Routes Generated for Norfolk-Rota Route, 12012010 (From Google Earth, 2011)

Tables 13–15 show sensitivity of routes from Pearl Harbor to Yokosuka. This origin-destination pair shows the greatest sensitivity, with some optimized routes over 5000 nm apart, for the same departure date. There are five departure dates (06162010, 10022010, 10162010, 11022010 and 12162010) in which the analysis route and the ensemble-average-optimized route are the same. This does not necessarily mean that all routes are close to each other; rather, there are some ensemble members whose routes may be far (almost 780 nm away for 10162010) from the reference route. Different ensemble members may produce dramatically different routes.

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis-optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis-optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
All Ensemble Members Average(StDev)	06022010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	06162010	17.8(68.9)	17.8(68.9)	137.1(57.1)	710.1(183.3)	710.1(183.3)	1633.1(128.8)
	07022010*	51.5(38.9)	42.5(35.3)	346.2(17.6)	230.4(74.5)	270.5(91.6)	6062.6(7.3)
	07162010*	22.5(70.8)	24.2(73.4)	224.2(54.4)	758.9(202.6)	758.9(210.1)	1821.3(149.4)
	08022010	63.1(2.6)	3.4(13.1)	6.3(11.4)	216.4(24.3)	272.8(70.4)	254.7(61.1)
	08162010	17.2(0.0)	0.2(1.0)	0.5(0.8)	94.3(7.9)	65.3(16.3)	61.2(14.3)
	09022010	14.6(40.7)	14.8(40.7)	98.8(31.0)	486.6(114.1)	486.6(117.8)	2426.4(15.9)
	09162010	49.9(26.2)	34.3(28.1)	219.9(16.8)	235.4(65.6)	244.5(70.6)	5731.1(15.7)
	10022010	16.6(62.0)	16.6(62.0)	143.1(52.0)	649.2(173.5)	649.2(173.5)	1680.0(126.0)
	10162010	51.1(109.8)	51.1(109.8)	472.6(79.4)	779.6(306.9)	779.6(306.9)	3740.4(249.4)
	11022010	35.0(92.7)	35.0(92.7)	301.5(71.1)	744.3(248.1)	744.3(248.1)	2793.6(185.7)
	11162010	41.6(155.7)	0.0(0.0)	162.3(120.7)	1306.7(349.2)	0.0(0.0)	1905.1(209.3)
	12022010	29.5(114.1)	259.7(8.3)	157.9(92.9)	1195.9(308.8)	742.2(24.4)	1725.3(150.0)
	12162010*	3.8(14.8)	4.1(15.3)	7.1(12.9)	281.7(72.7)	281.7(75.3)	263.1(63.1)

Table 13. For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Average of all Ensemble Members and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
Analysis-Optimized Route	06022010	0	NaN	0	0	NaN	0
	06162010	0	0	122.3	0	0	1134.4
	07022010*	0	49.4	345.8	0	162.4	6034.6
	07162010*	0	NaN	207.3	0	NaN	1261.2
	08022010	0	63.8	61.1	0	216.4	201.0
	08162010	0	17.2	17.1	0	94.3	90.5
	09022010	0	1.0	88.7	0	31.4	2372.1
	09162010	0	53.3	227.3	0	144.5	5725.3
	10022010	0	0	129.2	0	0	1208.5
	10162010	0	0	435.6	0	0	3113.3
	11022010	0	0	274.8	0	0	2234.6
	11162010	0	NaN	132.2	0	NaN	1068.0
	12022010	0	257.5	133.9	0	647.5	1144.3
	12162010*	0	0	3.8	0	0	18.7

Table 14. For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance (nm) from		
		Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
Average Environments-Optimized Route	06022010	NaN	0	0.0	NaN	0	0.0
	06162010	0	0	122.3	0	0	1134.4
	07022010*	49.4	0	337.9	162.4	0	6034.6
	07162010*	NaN	0	207.3	NaN	0	1261.2
	08022010	63.8	0	3.4	216.4	0	18.2
	08162010	17.2	0	0.2	94.3	0	4.1
	09022010	1.0	0	89.0	31.4	0	2372.1
	09162010	53.3	0	204.3	144.5	0	5707.5
	10022010	0	0	129.2	0	0	1208.5
	10162010	0	0	435.6	0	0	3113.3
	11022010	0	0	274.8	0	0	2234.6
	11162010	NaN	0	132.2	NaN	0	1068.0
	12022010	257.5	0	342.0	647.5	0	1615.8
	12162010*	0	0	3.8	0	0	18.7

Table 15. For Each Departure Date for the Pearl Harbor-Yokosuka Route, Route Average GC Distance and Maximum GC Distance From the Averaged Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

The fields in Tables 14 and 15 with “NaN” as the cell value mean that the optimized route used for comparison was not generated. Tables 13–15 show three departure dates for the Pearl Harbor-Yokosuka route that include an asterisk. Optimized routes for these departure dates, to include the analysis and the environment average routes, are shown in Figures 11–13.

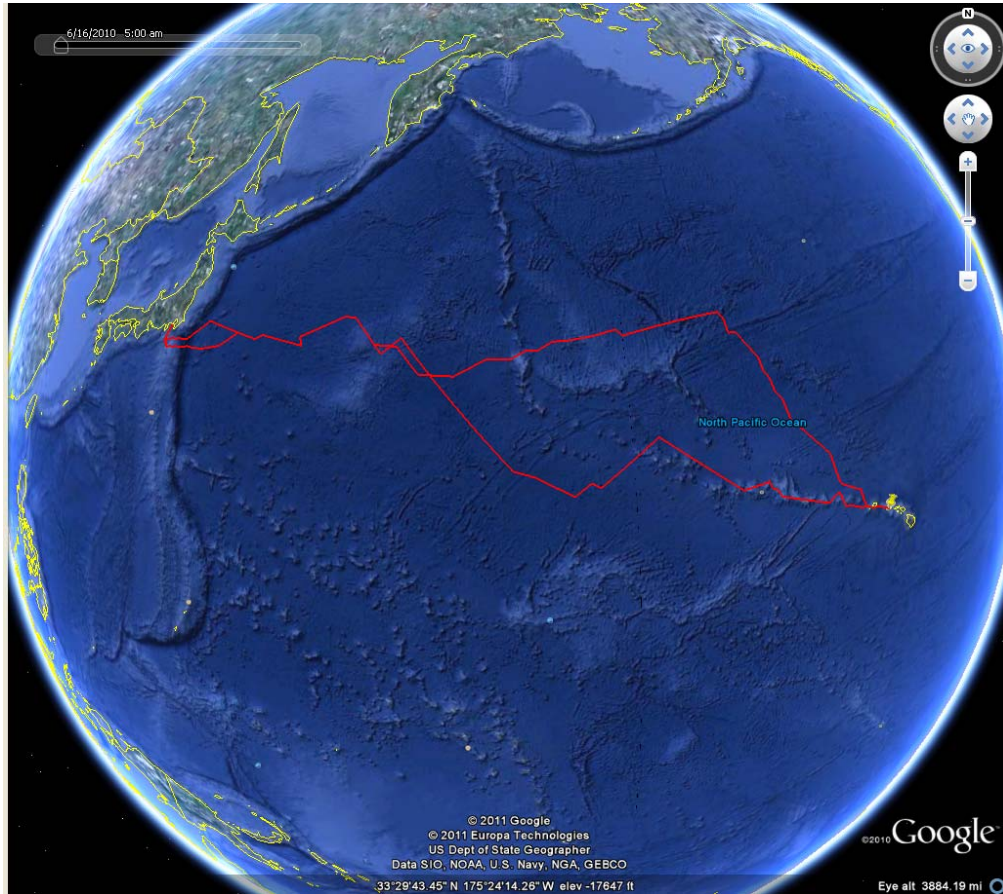


Figure 11. Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 06162010
(From Google Earth, 2011)



Figure 12. Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 07162010
(From Google Earth, 2011)

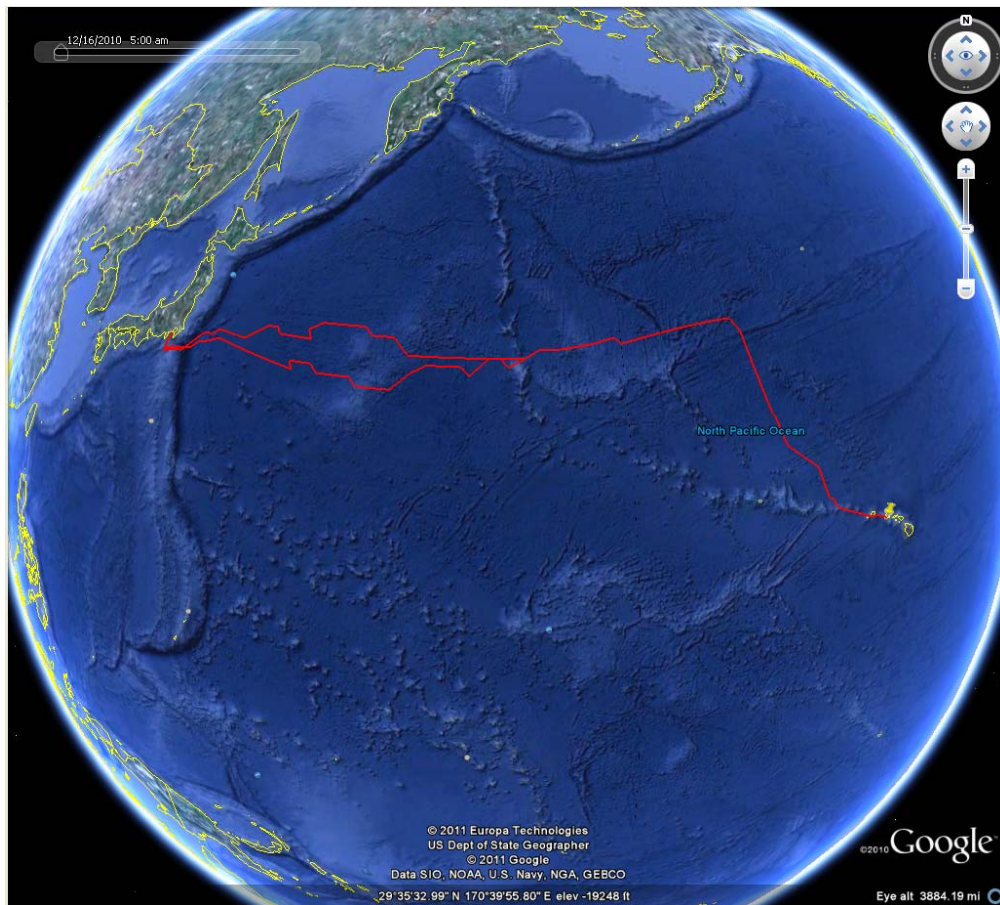


Figure 13. Optimized Routes Generated for Pearl Harbor-Yokosuka Route, 12162010
(From Google Earth, 2011)

Tables 16–18 show sensitivity results for routes from San Diego to Guam. There are only four departure dates (08032010, 09032010, 10032010, and 10172010) with any sensitivity. However, on these four dates, the optimized routes are very far apart—almost 800 nm for 10032010 departure date.

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance from		
		Analysis-optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis-optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
All Ensemble Members Average (StDev)	06032010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	06172010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	07032010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	07172010	NaN(NaN)	0.0(0.0)	0.0(0.0)	NaN(NaN)	0.0(0.0)	0.0(0.0)
	08032010*	71.3(31.6)	69.2(31.8)	200.4(10.3)	336.0(82.6)	336.0(85.4)	6174.8(26.6)
	08172010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	09032010*	18.9(73.2)	18.9(73.2)	35.3(63.5)	756.2(195.2)	756.2(195.2)	705.9(169.3)
	09172010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	10032010*	203.6(67.9)	133.2(96.2)	206.7(36.7)	604.6(111.6)	790.2(262.5)	2259.9(77.4)
	10172010*	195.0(20.1)	47.8(80.9)	176.6(48.3)	512.8(86.2)	555.9(206.2)	5029.9(31.6)
	11032010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	11172010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	12032010	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	12172010	NaN(NaN)	NaN(NaN)	NaN(NaN)	NaN(NaN)	NaN(NaN)	NaN(NaN)

Table 16. For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average of all Ensemble Members and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance from		
		Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
Analysis-Optimized Route	06032010	0	0	0	0	0	0
	06172010	0	0	0	0	0	0
	07032010	0	0	0	0	0	0
	07172010	0	NaN	0	0	NaN	0
	08032010*	0	21.2	189.3	0.0	116.7	6100.2
	08172010	0	0	0	0	0	0
	09032010*	0	0	18.9	0	0	50.2
	09172010	0	0	0	0	0	0
	10032010*	0	226.3	261.6	0	468.1	2086.3
	10172010*	0	190.8	279.2	0	512.8	4829.0
	11032010	0	0	0	0	0	0
	11172010	0	0	0	0	0	0
	12032010	0	0	0	0	0	0
	12172010	NaN	NaN	NaN	NaN	NaN	NaN

Table 17. For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average of the Analysis-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

	Departure Date (MMDDYYYY)	Route-Average GC Distance (nm) from			Maximum GC Distance from		
		Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route	Analysis- optimized Route	Average Environments- optimized Route	Average of Member- optimized Route
Average Environments-Optimized Route	06032010	0	0	0	0	0	0
	06172010	0	0	0	0	0	0
	07032010	0	0	0	0	0	0
	07172010	NaN	0	0	NaN	0	0
	08032010*	21.2	0	187.1	116.7	0	6100.2
	08172010	0	0	0	0	0	0
	09032010*	0	0	18.9	0	0	50.2
	09172010	0	0	0	0	0	0
	10032010*	226.3	0	192.9	468.1	0	2127.9
	10172010*	190.8	0	152.6	512.8	0	5009.1
	11032010	0	0	0	0	0	0
	11172010	0	0	0	0	0	0
	12032010	0	0	0	0	0	0
	12172010	NaN	NaN	NaN	NaN	NaN	NaN

Table 18. For Each Departure Date for the San Diego-Guam Route, Route Average GC Distance and Maximum GC Distance From the Average Environments-optimized Route and the Analysis-optimized Route, the Averaged Environments-optimized Route and the Average of Member-optimized Route

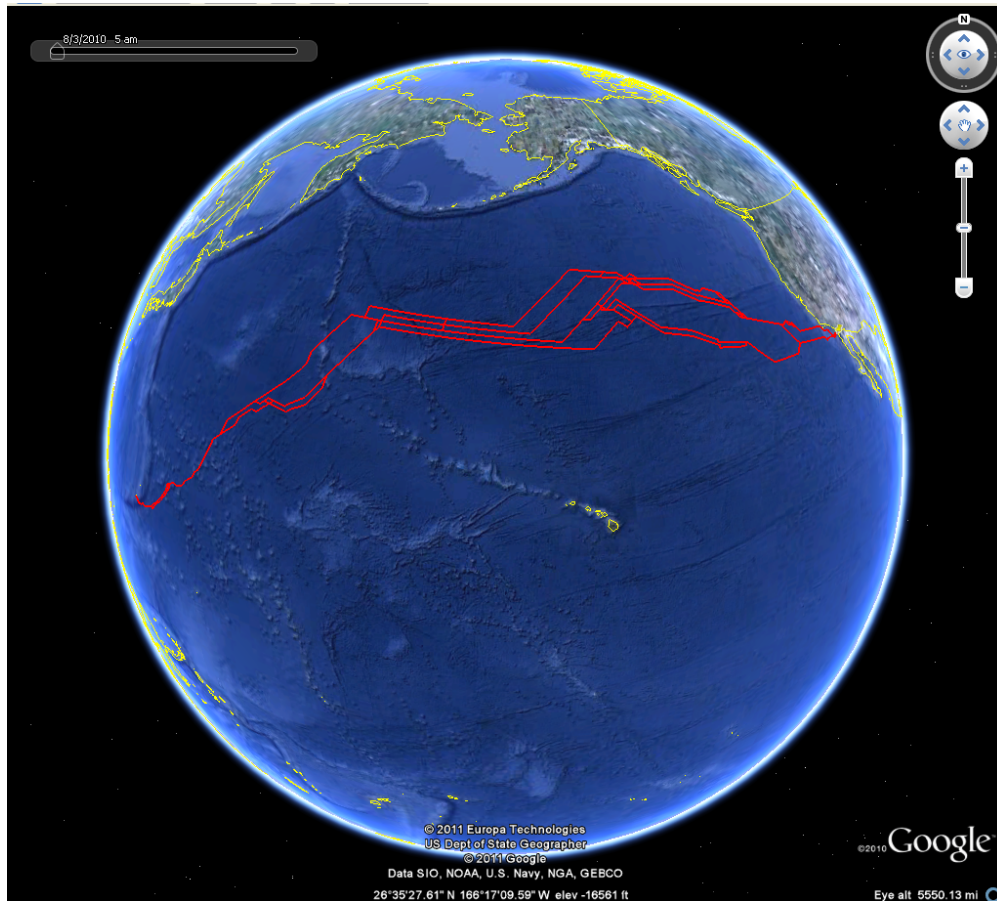


Figure 14. Optimized Routes Generated for San Diego-Guam Route, 08032010 (From Google Earth, 2011)

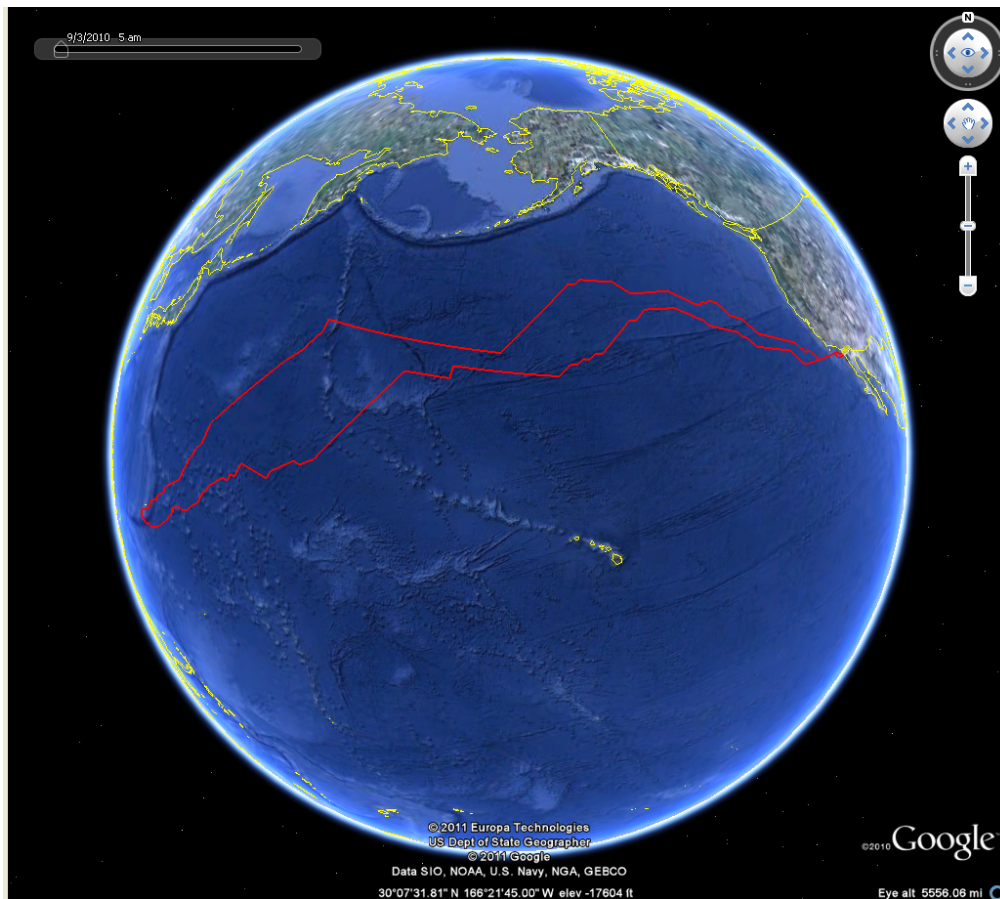


Figure 15. Optimized Routes Generated for San Diego-Guam Route, 09032010 (From Google Earth, 2011)

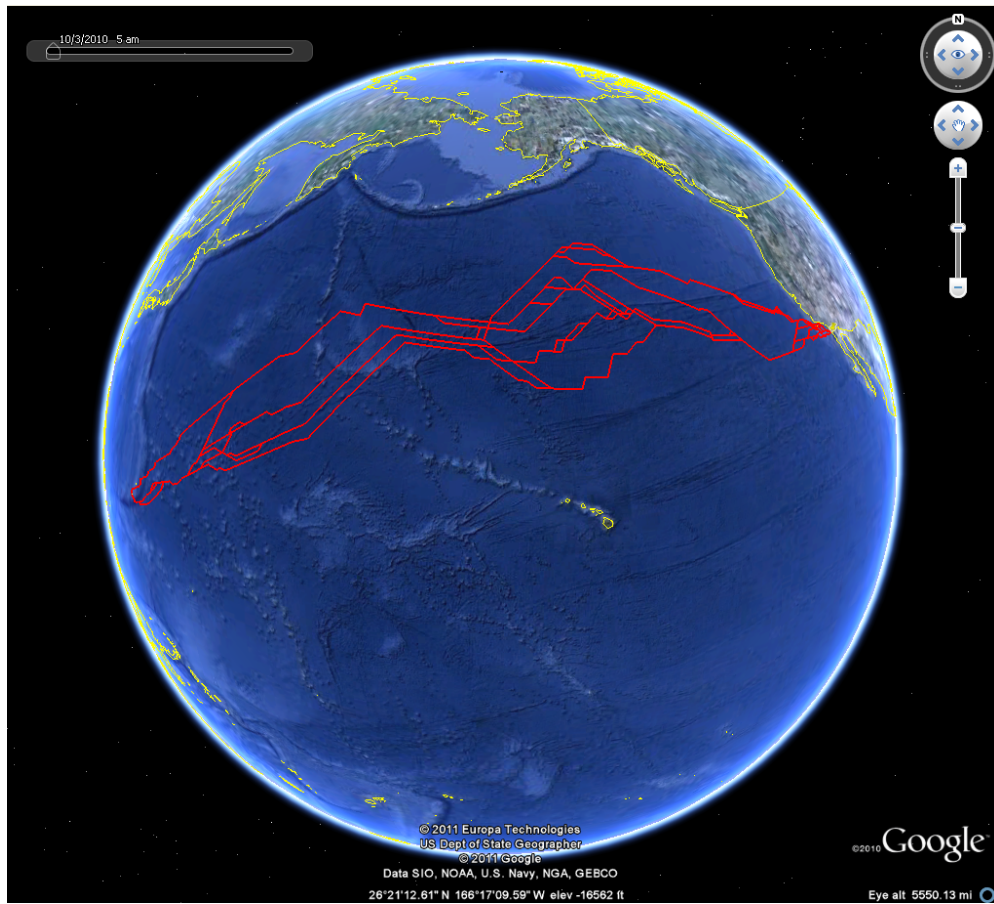


Figure 16. Optimized Routes Generated for San Diego-Guam Route, 10032010 (From Google Earth, 2011)

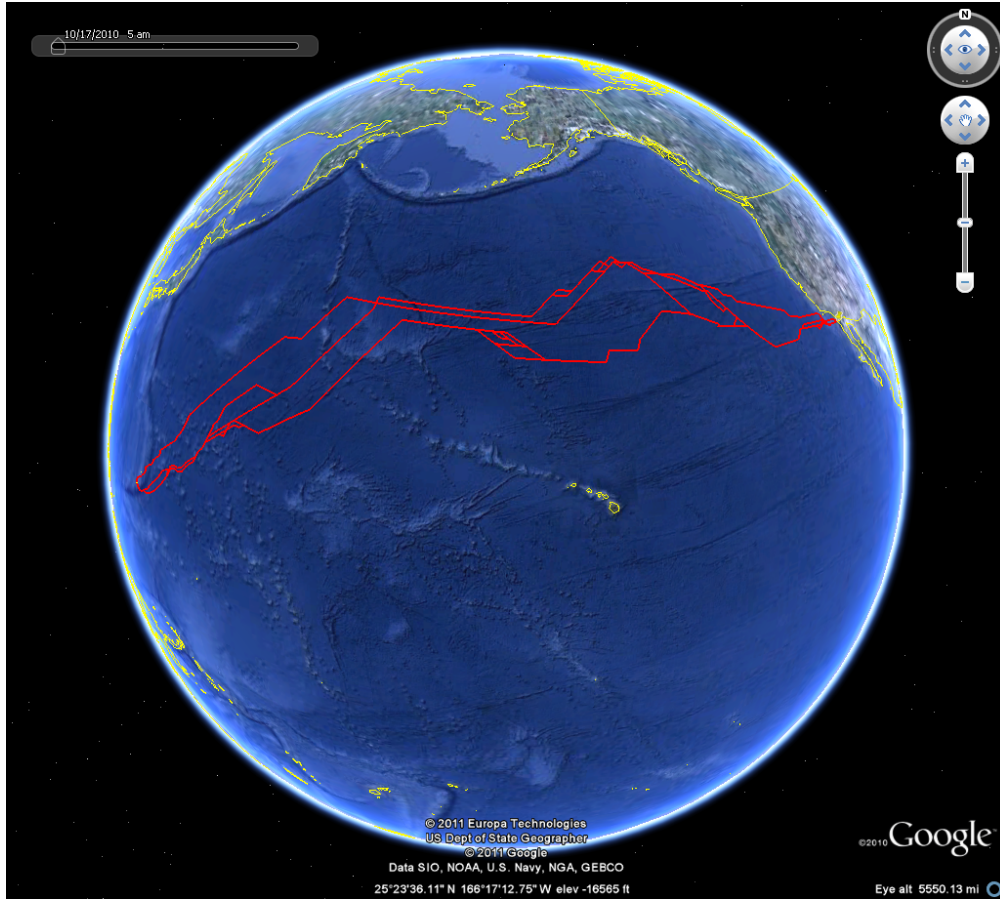


Figure 17. Optimized Routes Generated for San Diego-Guam Route, 10032010
(From Google Earth, 2011)

In some cases, the average of the all ensemble member routes produced larger average GC distances from the member-optimized routes than the analysis-optimized route or the environments-optimized routes. This is counterintuitive. The reason is that the average route consists of the Cartesian average position of each waypoint, while the distances between routes are calculated using GC distances between waypoints. Overall, the Norfolk-Rota and Pearl Harbor-Yokosuka routes are more sensitive to the environmental conditions during the time period indicated. The San Diego-Guam routes are the least sensitive to the environmental conditions. With only four departure dates with non-zero results, this means that the environmental conditions on the other departure dates have no effect on the route generated. Regardless of the environmental conditions, the routes generated are optimal in any environmental condition.

D. MEASURING ROBUSTNESS

The robustness metrics reflect how well the optimized route for a given environment origin-destination pair and start date measures up with respect to the safety thresholds when evaluated within other forecast environmental conditions.

In addition to the variables generated by STARS, the following variables were calculated as they will be used in measuring route safety:

$relative_wind(w_n, j)$	Wind speed experienced by ship while in motion.
$seas(w_n, j)$	The maximum of $sig_wave_height(w_n, j)$, $sea_height(w_n, j)$ and $swell_height(w_n, j)$.

Relative wind was calculated according to Equation 4.

$$\sqrt{wind_speed(w_n, j)^2 + s_n} + 2(wind_speed(w_n, j)) \times s_n \times \cos c_n \quad [4]$$

The safety thresholds utilized in STARS, as depicted in Appendix A, are 35 knots of wind speed, 65 knots of relative wind speed, and 25-foot seas (head, beam and following). The STARS output did not provide head, beam, and following seas. In evaluating the safety of routes, the operational threshold is 25-foot seas, using $seas(w_n, j)$. The notation $condition(w_n, j)$ will be used to generically represent any of the three METOC conditions used to measure safety, i.e., $wind_speed(w_n, j)$, $relative_wind(w_n, j)$ or $seas(w_n, j)$.

Tables 19–27 show summary statistics for safety-related METOC conditions and energy consumption relative to the same environment used for optimization. For each origin-destination pair and start date, these tables give the mean and maximum environmental conditions that would be experienced by the optimized route if the forecast

conditions hold, as well as the number of safety threshold exceedances experienced (as shown below in Equations 5–7, respectively), and the average amount of the exceedance, when it occurred.

$$\frac{1}{N} \sum_{n=1}^N condition(w_n^*(i), j) \quad [5]$$

$$\max_{n=1, \dots, N} condition(w_n^*(i), j) \quad [6]$$

$$\begin{aligned} \text{exceedances} &= \frac{1}{N} \sum_{n=1}^N X_n(i, j) \\ X_n(i, j) &= \begin{cases} 1 & \text{if } condition(w_n^*(i), j) > condition_threshold \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad [7]$$

Tables 19–21 show the overall safety of the optimized routes for each origin-destination pair, evaluated with respect to their own environment. The formulas for the mean and maximum values are shown in Equations 8 and 9, respectively. In the top third of Tables 19–21, mean and standard deviation with respect to the environments for which the routes were optimized (i) are shown.

$$\frac{1}{N} \sum_{n=1}^N condition(w_n^*(i), i) \quad [8]$$

$$\max_{n=1, \dots, N} (condition(w_n^*(i), i)) \quad [9]$$

		Absolute Winds, kts (35kt Threshold)						Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)			
	Departure Date (MMDDYYYY)	Energy Consumption (kWh)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)	
All Ensemble Members Mean (StdDev)	06012010	1853.3(10.2)	16.4(1.64)	26.5(1.77)	0.0(0.00)	NaN	34.6(1.24)	53.7(2.34)	0.0(0.00)	NaN	7.7(0.50)	11.1(0.74)	0.0(0.00)	NaN	
	06152010	1864.7(12.8)	10.6(1.50)	24.0(3.02)	0.0(0.00)	NaN	26.1(1.68)	39.2(2.75)	0.0(0.00)	NaN	5.4(0.60)	10.5(0.90)	0.0(0.00)	NaN	
	07012010	1823.0(9.0)	12.9(1.07)	27.1(3.54)	0.0(0.00)	NaN	26.6(0.94)	43.0(2.52)	0.0(0.00)	NaN	4.7(0.35)	10.8(1.08)	0.0(0.00)	NaN	
	07152010	1848.8(8.5)	14.1(1.32)	22.2(1.01)	0.0(0.00)	NaN	33.6(1.26)	49.3(1.96)	0.0(0.00)	NaN	6.2(0.56)	9.3(0.66)	0.0(0.00)	NaN	
	08012010	1810.2(11.6)	12.2(1.65)	26.8(3.88)	0.0(0.00)	NaN	25.0(1.16)	44.9(4.34)	0.0(0.00)	NaN	3.7(0.42)	9.1(1.62)	0.0(0.00)	NaN	
	08152010	1867.3(9.1)	9.7(1.19)	18.3(2.14)	0.0(0.00)	NaN	26.4(1.37)	41.4(2.67)	0.0(0.00)	NaN	5.2(0.33)	7.9(0.62)	0.0(0.00)	NaN	
	09012010	1826.5(7.0)	9.9(0.78)	19.6(2.12)	0.0(0.00)	NaN	28.4(1.25)	45.3(2.43)	0.0(0.00)	NaN	4.9(0.33)	13.9(1.31)	0.0(0.00)	NaN	
	09152010	1845.3(7.8)	11.4(2.02)	28.0(3.43)	0.0(0.00)	NaN	29.0(2.15)	53.6(6.38)	0.0(0.00)	NaN	5.8(0.62)	10.2(1.06)	0.0(0.00)	NaN	
	10012010	1944.0(19.1)	15.6(1.11)	27.2(2.06)	0.0(0.00)	NaN	32.0(1.64)	48.9(2.36)	0.0(0.00)	NaN	9.1(0.68)	17.8(1.54)	0.0(0.00)	NaN	
	10152010	1932.6(33.9)	18.9(1.22)	34.8(2.34)	0.0(0.00)	NaN	33.9(1.63)	59.7(3.49)	0.0(0.00)	NaN	10.9(0.83)	19.5(2.22)	0.0(0.00)	NaN	
	11012010	1890.9(29.2)	16.4(1.20)	35.9(4.44)	0.1(0.25)	0.2(0.41)	27.2(1.35)	46.9(2.74)	0.0(0.00)	NaN	7.3(0.53)	15.1(2.06)	0.0(0.00)	NaN	
	11152010	1975.2(44.8)	13.3(1.95)	36.7(4.77)	0.2(0.40)	1.0(0.70)	24.1(1.78)	51.7(6.47)	0.0(0.00)	NaN	7.1(0.83)	17.5(2.63)	0.0(0.00)	NaN	
12012010	2197.1(93.9)	18.3(1.95)	31.6(1.49)	0.0(0.00)	NaN	29.7(2.12)	57.2(4.63)	0.0(0.00)	NaN	11.7(1.30)	24.7(3.79)	0.0(0.00)	NaN		
12152010	2016.6(42.6)	17.1(6.99)	35.7(10.80)	0.1(0.25)	0.2(0.41)	30.7(12.15)	56.6(17.81)	0.0(0.00)	NaN	10.0(3.99)	20.8(6.48)	0.0(0.00)	NaN		
Analysis-Optimized Route	06012010	1853.3(10.2)	15.6	21.3	0	NaN	33.5	43.0	0	NaN	6.4	8.7	0	NaN	
	06152010	1864.7(12.8)	14.7	22.1	0	NaN	29.7	40.0	0	NaN	4.8	8.2	0	NaN	
	07012010	1823.0(9.0)	11.7	18.4	0	NaN	25.5	36.5	0	NaN	4.4	6.8	0	NaN	
	07152010	1848.8(8.5)	14.2	23.5	0	NaN	33.2	47.8	0	NaN	6.2	8.6	0	NaN	
	08012010	1810.2(11.6)	13.2	23.7	0	NaN	26.5	42.1	0	NaN	4.2	8.1	0	NaN	
	08152010	1867.3(9.1)	10.8	16.2	0	NaN	28.3	40.1	0	NaN	5.4	7.3	0	NaN	
	09012010	1826.5(7.0)	12.2	21.6	0	NaN	31.0	46.4	0	NaN	6.1	11.0	0	NaN	
	09152010	1845.3(7.8)	12.9	18.9	0	NaN	29.9	43.8	0	NaN	6.5	8.4	0	NaN	
	10012010	1944.0(19.1)	14.0	25.8	0	NaN	28.8	43.6	0	NaN	9.3	14.7	0	NaN	
	10152010	1932.6(33.9)	18.0	27.7	0	NaN	34.2	52.6	0	NaN	10.3	14.3	0	NaN	
	11012010	1890.9(29.2)	17.8	24.3	0	NaN	28.0	42.1	0	NaN	8.5	11.5	0	NaN	
	11152010	1975.2(44.8)	13.8	30.0	0	NaN	21.9	33.4	0	NaN	6.1	11.6	0	NaN	
12012010	2197.1(93.9)	22.1	30.7	0	NaN	30.1	46.3	0	NaN	14.5	25.9	1	0.85		
12152010	2016.6(42.6)	19.6	31.5	0	NaN	32.7	53.1	0	NaN	11.5	18.0	0	NaN		
Average-Environment-Optimized Route	06012010	1853.3(10.2)	16.4	21.5	0	NaN	35.4	46.3	0	NaN	7.7	9.9	0	NaN	
	06152010	1864.7(12.8)	10.1	15.4	0	NaN	26.8	32.2	0	NaN	5.4	8.5	0	NaN	
	07012010	1823.0(9.0)	12.1	15.7	0	NaN	26.3	38.3	0	NaN	4.5	7.3	0	NaN	
	07152010	1848.8(8.5)	13.7	19.2	0	NaN	34.1	46.6	0	NaN	6.2	7.6	0	NaN	
	08012010	1810.2(11.6)	11.4	16.3	0	NaN	25.4	40.8	0	NaN	3.5	5.7	0	NaN	
	08152010	1867.3(9.1)	9.4	12.8	0	NaN	28.0	50.9	0	NaN	5.3	6.5	0	NaN	
	09012010	1826.5(7.0)	9.7	15.3	0	NaN	28.8	36.4	0	NaN	5.0	10.8	0	NaN	
	09152010	1845.3(7.8)	11.3	15.9	0	NaN	29.5	40.3	0	NaN	6.0	7.4	0	NaN	
	10012010	1944.0(19.1)	14.5	20.0	0	NaN	33.1	42.8	0	NaN	9.0	14.0	0	NaN	
	10152010	1932.6(33.9)	18.1	31.5	0	NaN	31.9	50.2	0	NaN	10.8	15.4	0	NaN	
	11012010	1890.9(29.2)	16.8	23.2	0	NaN	26.5	41.0	0	NaN	7.5	9.9	0	NaN	
	11152010	1975.2(44.8)	11.4	21.0	0	NaN	23.5	38.6	0	NaN	7.2	10.9	0	NaN	
12012010	2197.1(93.9)	19.0	28.9	0	NaN	29.7	47.3	0	NaN	13.2	18.5	0	NaN		
12152010	2016.6(42.6)	19.5	27.2	0	NaN	37.8	50.5	0	NaN	11.3	16.2	0	NaN		

Table 19. Robustness of the Optimized Routes for Norfolk to Rota

	Departure Date (MMDDYYYY)	Energy Consumption (kWh)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)			
			Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)
All Ensemble Members Mean (StDev)	06022010	2219.4(14.8)	12.9(0.82)	32.4(3.80)	0.0(0.00)	NaN	28.0(1.19)	49.4(2.69)	0.0(0.00)	NaN	5.0(0.34)	11.7(1.30)	0.0(0.00)	NaN
	06162010	2320.0(37.5)	14.4(4.05)	30.0(6.80)	0.0(0.00)	NaN	23.3(6.25)	39.4(9.46)	0.0(0.00)	NaN	6.4(1.80)	14.1(3.09)	0.0(0.00)	NaN
	07022010	2225.4(19.0)	10.9(3.14)	22.2(4.84)	0.0(0.00)	NaN	24.2(6.54)	42.7(10.27)	0.0(0.00)	NaN	4.5(1.25)	9.9(2.16)	0.0(0.00)	NaN
	07162010	2194.6(23.1)	11.1(4.78)	26.6(7.54)	0.0(0.00)	NaN	24.0(9.60)	43.2(13.93)	0.0(0.00)	NaN	3.7(1.59)	10.6(2.70)	0.0(0.00)	NaN
	08022010	2215.8(16.9)	11.4(3.58)	18.8(5.04)	0.0(0.00)	NaN	26.4(7.54)	45.9(11.75)	0.0(0.00)	NaN	4.2(1.28)	7.1(1.86)	0.0(0.00)	NaN
	08162010	2216.1(16.3)	12.3(0.81)	24.5(2.16)	0.0(0.00)	NaN	29.4(1.06)	43.9(1.34)	0.0(0.00)	NaN	4.8(0.57)	10.9(1.52)	0.0(0.00)	NaN
	09022010	2196.7(7.8)	11.0(0.66)	19.9(2.04)	0.0(0.00)	NaN	28.4(0.90)	44.3(1.90)	0.0(0.00)	NaN	4.0(0.28)	7.5(0.55)	0.0(0.00)	NaN
	09162010	2250.1(9.2)	9.8(0.70)	18.2(0.62)	0.0(0.00)	NaN	27.4(0.81)	43.1(0.66)	0.0(0.00)	NaN	5.1(0.20)	9.1(0.59)	0.0(0.00)	NaN
	10022010	***	***	***	***	***	***	***	***	***	***	***	***	***
	10162010	2258.2(44.4)	14.1(1.16)	30.6(3.95)	0.0(0.00)	NaN	29.3(0.96)	51.6(4.36)	0.0(0.00)	NaN	7.1(0.96)	18.1(3.09)	0.0(0.00)	NaN
	11022010	2603.7(68.0)	15.2(4.16)	33.6(7.66)	0.0(0.00)	NaN	27.9(7.51)	51.0(11.37)	0.0(0.00)	NaN	10.2(2.80)	17.4(3.98)	0.0(0.00)	NaN
	11162010	2522.4(66.5)	16.5(2.24)	43.5(7.14)	0.7(1.40)	4.0(2.59)	30.5(2.67)	66.7(8.98)	0.1(0.25)	**	12.0(1.20)	27.7(3.76)	0.1(0.50)	**
Analysis-Optimized Route	12022010	2413.5(91.6)	22.3(7.13)	47.5(11.33)	1.8(2.21)	1.7(5.59)	34.6(10.38)	66.0(15.60)	0.1(0.25)	0.5(0.73)	12.4(3.96)	26.8(6.83)	0.5(1.19)	1.0(0.71)
	12162010	2360.8(62.0)	17.4(4.85)	36.0(7.82)	0.1(0.25)	0.5(0.71)	29.5(8.10)	53.2(11.61)	0.0(0.00)	NaN	9.4(2.58)	15.3(3.61)	0.0(0.00)	NaN
	06022010	2219.4(14.8)	14.1	28.3	0	NaN	28.1	47.5	0	NaN	5.8	10.5	0	NaN
	06162010	2320.0(37.5)	16.8	24.6	0	NaN	24.5	38.3	0	NaN	7.0	10.0	0	NaN
	07022010	2225.4(19.0)	12.2	20.8	0	NaN	26.1	41.7	0	NaN	4.5	6.9	0	NaN
	07162010	2194.6(23.1)	NaN	NaN	NaN	NaN	23.5	31.1	0	NaN	NaN	NaN	NaN	NaN
	08022010	2215.8(16.9)	11.7	18.2	0	NaN	28.9	38.8	0	NaN	5.1	7.2	0	NaN
	08162010	2216.1(16.3)	13.9	19.2	0	NaN	30.1	40.0	0	NaN	5.2	10.8	0	NaN
	09022010	2196.7(7.8)	10.6	13.4	0	NaN	28.8	36.6	0	NaN	4.3	6.8	0	NaN
	09162010	2250.1(9.2)	10.3	17.5	0	NaN	28.7	40.0	0	NaN	5.8	8.1	0	NaN
	10022010	2232.1(52.5)	15.3	21.8	0	NaN	27.0	37.6	0	NaN	6.7	11.6	0	NaN
	10162010	2258.2(44.4)	NaN	NaN	NaN	NaN	23.7	26.0	0	NaN	NaN	NaN	NaN	NaN
Average-Environment-Optimized Route	11022010	2603.7(68.0)	16.6	28.4	0.0	NaN	25.6	42.9	0	NaN	10.7	16.0	0	NaN
	11162010	2522.4(66.5)	NaN	NaN	NaN	NaN	23.8	29.5	0	NaN	NaN	NaN	NaN	NaN
	12022010	2413.5(91.6)	24.1	36.8	3	1.2	35.6	59.0	0	NaN	13.6	22.7	0	NaN
	12162010	2360.8(62.0)	18.7	27.1	0	NaN	33.2	47.0	0	NaN	9.9	13.7	0	NaN
	06022010	2219.4(14.8)	11.8	15.2	0	NaN	28.7	40.4	0	NaN	4.7	6.8	0	NaN
	06162010	2320.0(37.5)	14.8	23.3	0	NaN	29.5	43.0	0	NaN	6.7	10.0	0	NaN
	07022010	2225.4(19.0)	10.5	17.2	0	NaN	26.7	41.5	0	NaN	4.5	7.5	0	NaN
	07162010	2194.6(23.1)	12.6	15.1	0	NaN	28.4	41.3	0	NaN	4.2	4.8	0	NaN
	08022010	2215.8(16.9)	11.7	17.3	0	NaN	29.1	44.6	0	NaN	4.4	6.5	0	NaN
	08162010	2216.1(16.3)	11.7	18.8	0	NaN	29.8	38.7	0	NaN	4.8	8.8	0	NaN
	09022010	2196.7(7.8)	10.5	14.2	0	NaN	26.9	36.7	0	NaN	3.9	5.7	0	NaN
	09162010	2250.1(9.2)	9.2	17.1	0	NaN	27.0	42.1	0	NaN	4.9	7.4	0	NaN
	10022010	2232.1(52.5)	13.1	18.8	0	NaN	27.2	38.3	0	NaN	5.9	8.3	0	NaN
	10162010	2258.2(44.4)	13.6	18.6	0	NaN	28.8	42.8	0	NaN	7.3	13.2	0	NaN
	11022010	2603.7(68.0)	15.6	22.6	0	NaN	29.9	42.2	0	NaN	10.9	15.8	0	NaN
	11162010	2522.4(66.5)	15.6	26.7	0	NaN	30.6	41.2	0	NaN	11.8	15.1	0	NaN
	12022010	2413.5(91.6)	17.5	22.7	0	NaN	33.1	45.0	0	NaN	11.6	17.6	0	NaN
	12162010	2360.8(62.0)	18.6	27.1	0	NaN	33.1	43.7	0	NaN	10.2	14.3	0	NaN

Table 20. Robustness of the Optimized Routes for Pearl Harbor to Yokosuka

	Departure Date (MMDDYYYY)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)			
		Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)
All Ensemble Members Mean (StdDev)	06032010	11.1(4.49)	32.7(9.35)	0.0(0.00)	NaN	22.4(8.76)	54.1(15.45)	0.0(0.00)	NaN	5.9(2.49)	21.3(4.97)	0.0(0.00)	NaN
	06172010	17.1(4.76)	31.0(6.94)	0.0(0.00)	NaN	21.2(5.68)	49.0(10.78)	0.0(0.00)	NaN	8.1(2.27)	14.5(3.37)	0.0(0.00)	NaN
	07032010	17.6(1.26)	34.2(3.00)	0.0(0.00)	NaN	26.3(0.57)	47.8(0.00)	0.0(0.00)	NaN	8.6(0.69)	15.8(1.24)	0.0(0.00)	NaN
	07172010	9.5(3.81)	21.2(6.76)	0.0(0.00)	NaN	22.1(8.66)	39.7(12.51)	0.0(0.00)	NaN	3.8(1.51)	7.9(2.30)	0.0(0.00)	NaN
	08032010	11.6(1.01)	18.3(1.32)	0.0(0.00)	NaN	23.5(0.76)	37.3(2.26)	0.0(0.00)	NaN	4.8(0.29)	7.7(0.72)	0.0(0.00)	NaN
	08172010	8.0(2.30)	16.6(3.82)	0.0(0.00)	NaN	23.5(6.31)	39.5(9.43)	0.0(0.00)	NaN	3.4(0.93)	6.5(1.49)	0.0(0.00)	NaN
	09032010	13.0(3.71)	23.7(5.55)	0.0(0.00)	NaN	22.2(6.01)	49.6(12.64)	0.0(0.00)	NaN	6.0(1.68)	11.8(2.46)	0.0(0.00)	NaN
	09172010	13.5(1.21)	24.9(1.85)	0.0(0.00)	NaN	23.5(0.79)	42.5(2.50)	0.0(0.00)	NaN	7.5(0.76)	14.7(1.03)	0.0(0.00)	NaN
	10032010	15.1(1.39)	34.4(3.57)	0.0(0.00)	NaN	26.1(0.97)	56.6(5.93)	0.0(0.00)	NaN	8.3(0.55)	16.0(1.83)	0.0(0.00)	NaN
	10172010	15.3(1.54)	30.6(3.05)	0.0(0.00)	NaN	26.1(0.85)	52.0(4.19)	0.0(0.00)	NaN	9.0(0.47)	16.5(1.11)	0.0(0.00)	NaN
	11032010	14.3(5.99)	38.2(11.91)	0.2(0.41)	1.1(1.31)	21.2(8.31)	43.6(13.47)	0.0(0.00)	NaN	11.1(4.60)	23.8(6.71)	0.0(0.00)	NaN
	11172010	16.6(0.56)	37.9(3.08)	0.3(0.58)	1.4(1.33)	26.0(0.91)	52.7(4.14)	0.0(0.00)	NaN	11.9(0.57)	20.8(1.11)	0.0(0.00)	NaN
	12032010	21.7(1.81)	56.9(6.43)	1.9(1.82)	4.1(2.72)	30.6(1.51)	63.8(3.91)	0.0(0.00)	NaN	14.4(1.04)	31.5(3.01)	2.6(1.79)	0.4(1.74)
Analysis-Optimized Route	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	06032010	12.8	20.3	0	NaN	26.8	41.1	0	NaN	5.8	10.8	0	NaN
	06172010	16.7	39.1	1	4.1	23.0	51.2	0	NaN	7.6	14.6	0	NaN
	07032010	19.3	32.7	0	NaN	27.3	47.8	0	NaN	8.4	13.8	0	NaN
	07172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	08032010	11.7	15.5	0	NaN	25.0	37.9	0	NaN	4.6	6.5	0	NaN
	08172010	NaN	NaN	NaN	NaN	24.7	29.0	0	NaN	NaN	NaN	NaN	NaN
	09032010	13.3	24.1	0	NaN	23.7	49.6	0	NaN	5.6	9.4	0	NaN
	09172010	14.6	26.2	0	NaN	24.8	36.3	0	NaN	7.9	11.9	0	NaN
	10032010	13.4	27.4	0	NaN	26.7	42.0	0	NaN	8.0	11.8	0	NaN
	10172010	15.9	30.6	0	NaN	26.0	38.7	0	NaN	8.5	12.7	0	NaN
	11032010	19.3	28.2	0	NaN	25.2	48.2	0	NaN	12.2	16.2	0	NaN
	11172010	20.5	40.5	2	5.5	29.5	57.4	0	NaN	15.3	31.5	4	1.4
Average-Environment-Optimized Route	12032010	16.0	37.1	1	2.1	26.3	54.1	0	NaN	11.1	18.8	0	NaN
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	06032010	11.6	18.9	0	NaN	25.3	37.4	0	NaN	6.6	9.9	0	NaN
	06172010	17.2	24.3	0	NaN	28.4	41.9	0	NaN	8.3	11.1	0	NaN
	07032010	16.6	23.7	0	NaN	26.2	47.8	0	NaN	8.3	12.7	0	NaN
	07172010	10.5	19.5	0	NaN	25.5	36.0	0	NaN	4.4	6.2	0	NaN
	08032010	11.8	16.0	0	NaN	22.5	34.3	0	NaN	4.9	6.5	0	NaN
	08172010	8.2	13.5	0	NaN	25.4	36.1	0	NaN	3.6	5.3	0	NaN
	09032010	13.4	20.3	0	NaN	23.6	49.6	0	NaN	6.4	8.4	0	NaN
	09172010	12.3	17.5	0	NaN	22.3	34.1	0	NaN	7.2	12.7	0	NaN
	10032010	15.2	22.5	0	NaN	26.0	38.1	0	NaN	8.6	10.8	0	NaN
	10172010	14.4	19.7	0	NaN	25.1	41.6	0	NaN	8.9	13.8	0	NaN
	11032010	15.3	27.0	0	NaN	24.4	36.9	0	NaN	12.3	16.0	0	NaN
	11172010	20.2	32.7	0	NaN	30.2	52.2	0	NaN	14.1	25.4	3	-0.9
	12032010	15.9	26.9	0	NaN	25.6	42.4	0	NaN	11.6	17.9	0	NaN
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 21. Robustness of the Optimized Routes for San Diego to Guam

Tables 22–24 show what happens when the routes optimized with respect to a given environmental forecast encounter the best guess for the actual METOC conditions, which is the analysis environment. For Tables 22–24, routes are evaluated with respect to analysis, so the mean is given by:

$$\frac{1}{M'} \sum_{i=1}^i \left(\frac{1}{N} \sum_{n=1}^N condition(w_n^*(i), j) \right), j = \text{analysis} \quad [10]$$

For Tables 22-24, routes are evaluated with respect to analysis, so the max is given by:

$$\max_{i=1, \dots, M'} \left(\max_{n=1, \dots, N} \left(condition(w_n^*(i), j) \right) \right), j = \text{analysis} \quad [11]$$

	Departure Date (MMDDYYYY)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)				Energy Consumption (khp)	
		mean	max	exceedances (number)	exceedances (kts)	mean	max	exceedances (number)	exceedances (kts)	mean	max	exceedances (number)	exceedances (ft)	mean over route	max over route
Environment-Analysis Route	06012010	16.5	25.5	0	NaN	34.0	49.1	0	NaN	6.8	9.8	0	NaN	1841.8	1849.9
	06152010	18.4	30.2	0	NaN	32.2	46.2	0	NaN	5.5	10.7	0	NaN	1880.8	1887.2
	07012010	12.3	19.6	0	NaN	26.3	38.8	0	NaN	4.5	7.2	0	NaN	1822.9	1827.4
	07152010	14.0	23.5	0	NaN	33.0	47.8	0	NaN	6.2	8.6	0	NaN	1842.5	1846.2
	08012010	13.3	23.7	0	NaN	25.1	42.1	0	NaN	4.2	8.1	0	NaN	1819.2	1821.8
	08152010	10.7	16.3	0	NaN	28.2	44.5	0	NaN	5.4	7.4	0	NaN	1853.5	1860.7
	09012010	13.0	24.7	0	NaN	31.6	49.2	0	NaN	6.3	11.3	0	NaN	1845.4	1850.4
	09152010	13.6	22.0	0	NaN	30.3	50.1	0	NaN	7.4	14.9	0	NaN	1884.0	1900.5
	10012010	14.5	25.8	0	NaN	29.2	45.8	0	NaN	9.2	15.7	0	NaN	1956.2	1977.4
	10152010	17.8	29.6	0	NaN	34.1	54.2	0	NaN	10.0	14.7	0	NaN	1902.3	1919.8
	11012010	17.6	30.0	0	NaN	27.8	42.1	0	NaN	8.5	14.2	0	NaN	1940.9	1984.8
	11152010	12.7	30.0	0	NaN	23.7	45.7	0	NaN	6.5	12.4	0	NaN	1949.2	1964.7
	12012010	20.0	30.7	0	NaN	30.4	53.6	0	NaN	13.2	25.9	0.3	**	2328.2	2466.7
	12152010	18.1	40.5	0.4	**	30.6	53.1	0	NaN	9.8	20.9	0	NaN	1802.3	2079.1

Table 22. Optimized Routes for Norfolk to Rota Under Actual METOC Conditions

	Departure Date (MMDDYYYY)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)				Energy Consumption (kWh)	
		Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)	Mean over Route	Maximum over Route
Environment-Analysis Route	06022010	14.1	28.3	0	NaN	28.1	47.5	0	NaN	5.8	10.5	0	NaN	2224.9	2224.9
	06162010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	07022010	11.5	24.5	0	NaN	23.8	41.7	0	NaN	4.4	8.6	0	NaN	2079.4	2224.1
	07162010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	08022010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	08162010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	09022010	10.6	22.2	0	NaN	28.6	48.0	0	NaN	4.4	9.6	0	NaN	2198.2	2223.7
	09162010	10.7	20.7	0	NaN	28.2	40.8	0	NaN	5.8	8.1	0	NaN	2268.5	2275.7
	10022010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	10162010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	11022010	15.5	29.4	0	NaN	24.7	47.1	0	NaN	9.9	16.0	0	NaN	2423.8	2605.8
	11162010	15.0	24.1	0	NaN	29.8	43.0	0	NaN	10.8	16.1	0	NaN	2441.8	2492.9
	12022010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	12162010	**	**	**	**	**	**	**	**	**	**	**	**	**	**

Table 23. Optimized Routes for Pearl Harbor to Yokosuka Under Actual METOC Conditions

	Departure Date (MMDDYYYY)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)				Energy Consumption (kWh)	
		Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)	Mean over Route	Maximum over Route
Environment-Analysis Route	06032010	11.2	20.3	0	NaN	23.5	41.1	0	NaN	5.1	10.8	0	NaN	3149.6	3599.6
	06172010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	07032010	19.3	32.7	0	NaN	27.3	47.8	0	NaN	8.4	13.8	0	NaN	3729.5	3729.5
	07172010	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	08032010	11.3	16.4	0	NaN	25.6	38.3	0	NaN	4.6	6.8	0	NaN	3538.8	3551.5
	08172010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	09032010	12.4	24.1	0	NaN	22.4	49.6	0	NaN	5.3	9.4	0	NaN	3373.2	3636.3
	09172010	14.6	26.2	0	NaN	24.8	36.3	0	NaN	7.9	11.9	0	NaN	3726.0	3726.0
	10032010	15.2	31.2	0	NaN	25.9	55.1	0	NaN	8.7	12.6	0	NaN	3781.7	3846.6
	10172010	16.7	41.0	1.3	NaN	26.2	49.8	0	NaN	8.5	14.8	0	NaN	3802.5	3834.3
	11032010	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	11172010	16.0	37.1	1	2.11	26.3	54.1	0	NaN	11.1	18.8	0	NaN	3908.2	3908.2
	12032010	20.5	40.5	2	5.49	29.5	57.4	0	NaN	15.3	31.5	4	1.4	4180.0	4180.0
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 24. Optimized Routes for San Diego to Guam Under Actual METOC Conditions

Tables 25–27 show what happens when routes, optimized with respect to one forecast environment are evaluated with respect to environments represented by the 16 ensemble members. Throughout, means are taken with respect to all ensemble members, as in Equation 12:

$$\frac{1}{M-1} \sum_{\substack{j=1 \\ j \neq i}}^M \left(\frac{1}{N} \sum_{n=1}^N condition(w_n^*(i), j) \right) \quad [12]$$

		Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, ft (25ft Threshold)				Energy Consumption	
	Departure Date (MMDDYYYY)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)	Mean over Route	Maximum over Route
All Ensemble Members Mean (StDev)	06022010	12.8(0.08)	32.0(1.54)	0.0(0.00)	NaN	27.8(0.23)	49.2(0.47)	0.0(0.00)	NaN	5.0(0.04)	11.5(0.75)	0.0(0.00)	NaN	2217.3(3.41)	2256.4(3.62)
	06162010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	07022010	11.0(3.06)	23.2(5.54)	0.0(0.00)	NaN	24.3(6.54)	42.7(10.52)	0.0(0.00)	NaN	4.5(1.22)	11.4(2.59)	0.0(0.00)	NaN	2088.5(556.98)	2286.2(563.34)
	07162010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	08022010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	08162010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	09022010	11.2(0.51)	21.6(0.57)	0.0(0.00)	NaN	28.4(0.42)	54.8(4.07)	0.0(0.00)	NaN	4.1(0.22)	9.1(0.44)	0.0(0.00)	NaN	2198.2(2.26)	2235.0(5.73)
	09162010	9.9(0.46)	23.2(2.09)	0.0(0.00)	NaN	27.5(0.34)	43.1(0.05)	0.0(0.00)	NaN	5.1(0.15)	10.1(0.54)	0.0(0.00)	NaN	2252.6(3.87)	2285.2(5.43)
	10022010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	10162010	14.0(1.11)	33.0(1.11)	0.0(0.00)	NaN	29.3(0.19)	51.6(0.90)	0.0(0.00)	NaN	7.1(0.75)	18.1(2.61)	0.0(0.00)	NaN	2259.2(28.96)	2340.0(45.11)
	11022010	15.4(4.12)	36.8(9.35)	0.2(0.08)	1.1(0.32)	28.0(7.49)	51.0(12.68)	0.0(0.00)	NaN	10.2(2.79)	17.4(4.31)	0.0(0.00)	NaN	2443.2(654.06)	2701.5(672.01)
	11162010	16.4(1.28)	43.5(3.67)	0.8(0.22)	4.4(0.28)	30.2(0.82)	66.7(6.09)	0.1(0.02)	1.7(0.00)	11.9(0.70)	27.7(2.91)	0.1(0.05)	2.7(0.00)	2521.8(8.00)	2662.0(11.77)
	12022010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	12162010	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Analysis-Optimized Route	06022010	12.6	26.2	0	NaN	28.4	49.4	0	NaN	4.8	8.2	0	NaN	2212.3	2221.4
	06162010	15.6	31.7	0	NaN	24.9	40.2	0	NaN	6.9	14.1	0	NaN	2324.1	2385.7
	07022010	11.5	21.2	0	NaN	26.6	42.7	0	NaN	4.7	9.6	0	NaN	2227.0	2251.2
	07162010	17.5	90.0	0.1	55.0	27.6	67.6	0.1	2.6	4.2	8.4	0	NaN	2198.2	2219.7
	08022010	12.5	19.9	0	NaN	29.9	43.6	0	NaN	4.6	7.2	0	NaN	2295.4	2308.1
	08162010	12.2	24.5	0	NaN	29.6	43.1	0	NaN	4.9	11.0	0	NaN	2262.7	2289.6
	09022010	11.1	19.9	0	NaN	28.6	38.5	0	NaN	4.0	7.5	0	NaN	2198.1	2213.2
	09162010	9.5	18.8	0	NaN	27.6	43.1	0	NaN	5.2	10.1	0	NaN	2254.2	2269.5
	10022010	13.6	21.0	0	NaN	27.6	41.9	0	NaN	5.8	11.0	0	NaN	2261.2	2287.3
	10162010	14.5	30.6	0	NaN	29.2	51.6	0	NaN	7.5	18.1	0	NaN	2273.2	2340.0
	11022010	16.5	36.8	0.2	1.2	29.6	51.0	0	NaN	11.1	17.4	0	NaN	2630.7	2701.5
	11162010	17.1	43.5	0.9	4.7	30.1	66.7	0.1	1.7	12.3	27.7	0.2	2.7	2503.3	2615.0
	12022010	24.7	47.5	1.9	4.1	39.1	66.0	0.1	1.0	13.9	26.8	0.7	1.2	2453.1	2556.8
	12162010	19.4	44.8	0.3	3.3	32.9	63.1	0	NaN	10.5	24.9	0	NaN	2398.9	2466.8
Average-Environment-Optimized Route	06022010	12.8	32.4	0	NaN	27.9	49.4	0	NaN	4.9	11.7	0	NaN	2215.4	2257.7
	06162010	15.6	31.7	0	NaN	24.9	40.2	0	NaN	6.9	14.1	0	NaN	2324.1	2385.7
	07022010	10.9	22.0	0	NaN	26.6	42.7	0	NaN	4.6	9.7	0	NaN	2221.9	2238.0
	07162010	12.9	22.8	0	NaN	28.3	42.3	0	NaN	4.3	8.4	0	NaN	2203.2	2221.6
	08022010	12.4	18.8	0	NaN	29.3	45.9	0	NaN	4.5	7.1	0	NaN	2224.7	2235.5
	08162010	12.3	24.5	0	NaN	29.6	43.9	0	NaN	4.9	10.9	0	NaN	2220.9	2248.7
	09022010	11.1	19.9	0	NaN	28.5	38.5	0	NaN	4.0	7.5	0	NaN	2198.1	2212.8
	09162010	9.8	23.2	0	NaN	27.4	43.1	0	NaN	5.0	9.1	0	NaN	2249.7	2265.5
	10022010	13.7	25.0	0	NaN	27.8	41.9	0	NaN	6.0	12.1	0	NaN	2270.6	2297.2
	10162010	14.5	30.6	0	NaN	29.2	51.6	0	NaN	7.5	18.1	0	NaN	2273.2	2340.0
	11022010	16.5	36.8	0.2	1.2	29.6	51.0	0	NaN	11.1	17.4	0	NaN	2630.7	2701.5
	11162010	16.5	43.5	0.6	4.8	30.5	66.7	0.1	1.7	11.9	27.7	0.2	2.7	2508.1	2645.1
	12022010	18.3	35.7	0.1	0.7	33.0	55.8	0	NaN	11.8	26.0	0.1	1.0	2509.9	2666.0
	12162010	19.3	44.8	0.3	3.3	32.9	63.1	0	NaN	10.5	24.9	0	NaN	2400.0	2466.8

Table 26. Overall Mean and Maximum Safety Experiences Along Pearl Harbor to Yokosuka Routes

	Departure Date (MMDDYY)	Absolute Winds, kts (35kt Threshold)				Relative Winds, kts (65kt Threshold)				Seas, 'ft (25ft Threshold)				Energy Consumption (kWh)	
		Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (kts)	Mean	Max	Exceedances (Number)	Exceedances (ft)	Mean over Route	Maximum over Route
All Ensemble Members Mean (SDist)	06032010	11.2(4.36)	22.7(11.12)	0.0(0.00)	NaN	22.2(8.68)	54.1(13.40)	0.0(0.00)	NaN	6.1(2.38)	21.3(7.27)	0.0(0.00)	NaN	3222.0(1257.74)	3861.1(1316.96)
	06172010	17.0(4.54)	31.0(7.72)	0.0(0.00)	NaN	21.3(5.69)	49.0(12.24)	0.0(0.00)	NaN	8.0(2.15)	14.5(3.33)	0.0(0.00)	NaN	3541.4(944.39)	3882.7(970.19)
	07032010	17.6(3.08)	34.2(0.04)	0.0(0.00)	NaN	26.3(0.04)	47.8(1.00)	0.0(0.00)	NaN	8.6(0.05)	15.8(0.16)	0.0(0.00)	NaN	3772.3(3.34)	3861.4(8.71)
	07172010	9.6(4.74)	21.2(7.25)	0.0(0.00)	NaN	22.2(8.66)	59.1(14.54)	0.0(0.00)	NaN	4.9(1.51)	7.9(2.38)	0.0(0.00)	NaN	3126.9(1218.07)	3575.4(1221.29)
	08032010	12.1(3.99)	26.4(2.07)	0.0(0.00)	NaN	23.6(0.31)	40.9(2.80)	0.0(0.00)	NaN	4.9(0.39)	9.6(0.39)	0.0(0.00)	NaN	3569.3(3.34)	3654.6(19.70)
	08172010	8.2(2.18)	16.6(4.15)	0.0(0.00)	NaN	23.7(6.32)	41.4(12.00)	0.0(0.00)	NaN	3.5(0.93)	8.9(2.11)	0.0(0.00)	NaN	3305.1(881.37)	3575.7(886.02)
	09032010	13.0(3.52)	23.7(5.92)	0.0(0.00)	NaN	22.2(5.94)	49.6(12.50)	0.0(0.00)	NaN	6.0(1.64)	11.8(3.32)	0.0(0.00)	NaN	3422.7(912.73)	3694.0(922.24)
	09172010	13.5(3.08)	24.9(0.19)	0.0(0.00)	NaN	23.9(0.05)	42.5(1.19)	0.0(0.00)	NaN	7.5(0.05)	14.7(0.18)	0.0(0.00)	NaN	3710.5(2.49)	3765.0(0.49)
	10032010	16.2(2.73)	49.0(4.93)	0.4(0.20)	3.5(1.06)	25.9(0.51)	61.4(7.09)	0.0(0.00)	NaN	8.9(0.36)	25.0(3.24)	0.0(0.00)	NaN	3787.6(20.94)	3950.1(44.39)
	10172010	15.5(1.14)	34.6(1.54)	0.0(0.00)	NaN	25.9(0.33)	52.0(1.88)	0.0(0.00)	NaN	9.1(0.15)	17.0(0.32)	0.0(0.00)	NaN	3926.3(21.60)	3991.4(43.05)
	11032010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
	11172010	16.6(1.04)	37.9(0.57)	0.3(0.04)	1.4(0.24)	26.0(0.06)	52.7(1.00)	0.0(0.00)	NaN	11.9(0.04)	20.8(0.30)	0.0(0.00)	NaN	3996.1(6.14)	4225.5(35.09)
	12032010	21.7(1.12)	56.9(1.10)	1.9(0.12)	4.1(0.27)	30.6(0.10)	63.8(1.46)	0.0(0.00)	NaN	14.4(0.07)	31.5(0.75)	2.6(0.12)	1.4(0.14)	4126.0(5.92)	4245.3(7.22)
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Average-Optimized Route	06032010	12.8	32.7	0	NaN	25.4	54.1	0	NaN	7.0	21.3	0	NaN	3683.6	3861.1
	06172010	18.2	31.0	0	NaN	22.7	49.0	0	NaN	8.6	14.5	0	NaN	3777.9	3882.7
	07032010	17.6	34.2	0	NaN	26.3	47.8	0	NaN	8.6	15.8	0	NaN	3772.3	3861.4
	07172010	10.9	21.2	0	NaN	25.3	39.7	0	NaN	4.4	7.9	0	NaN	3566.1	3575.4
	08032010	12.7	22.8	0	NaN	22.2	36.8	0	NaN	5.1	9.6	0	NaN	3566.1	3624.3
	08172010	8.8	16.6	0	NaN	23.6	39.5	0	NaN	3.7	5.5	0	NaN	3527.4	3537.3
	09032010	14.9	22.7	0	NaN	23.6	49.6	0	NaN	6.5	11.8	0	NaN	3649.2	3694.0
	09172010	13.5	24.9	0	NaN	23.5	42.5	0	NaN	7.5	14.7	0	NaN	3710.7	3765.0
	10032010	16.5	49.0	0.8	4.4	26.2	58.6	0	NaN	8.7	25.3	0	NaN	3813.4	3987.5
	10172010	15.9	36.2	0.1	3.3	25.0	48.1	0	NaN	10.1	13.3	0	NaN	3916.4	4035.9
	11032010	16.5	36.2	0.2	1.6	24.1	45.4	0	NaN	12.9	23.8	0	NaN	4091.9	4320.9
	11172010	16.6	37.9	0.3	1.4	26.0	52.7	0	NaN	11.9	20.8	0	NaN	3996.1	4225.5
	12032010	21.7	56.9	1.9	4.1	30.6	63.8	0	NaN	14.4	31.5	2.6	1.4	4126.0	4245.3
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Average-Environment-Optimized Route	06032010	12.8	32.7	0	NaN	25.5	54.1	0	NaN	6.9	21.3	0	NaN	3677.3	3861.1
	06172010	18.2	31.0	0	NaN	22.7	49.0	0	NaN	8.6	14.5	0	NaN	3777.9	3882.7
	07032010	17.6	34.2	0	NaN	26.3	47.8	0	NaN	8.6	15.8	0	NaN	3772.3	3861.4
	07172010	10.9	21.2	0	NaN	25.3	39.7	0	NaN	4.4	7.9	0	NaN	3566.1	3575.4
	08032010	12.5	22.8	0	NaN	23.1	40.5	0	NaN	5.0	9.6	0	NaN	3562.6	3624.3
	08172010	8.8	16.6	0	NaN	25.2	39.5	0	NaN	3.7	5.5	0	NaN	3527.4	3537.3
	09032010	14.9	22.7	0	NaN	23.6	49.6	0	NaN	6.5	11.8	0	NaN	3649.2	3694.0
	09172010	13.5	24.9	0	NaN	23.5	42.5	0	NaN	7.5	14.7	0	NaN	3710.7	3765.0
	10032010	16.5	42.1	0.4	2.6	26.4	59.1	0	NaN	9.0	22.8	0	NaN	3762.6	3912.7
	10172010	15.4	36.6	0	NaN	26.0	52.8	0	NaN	9.1	13.2	0	NaN	3815.9	3966.7
	11032010	16.5	36.2	0.2	1.6	24.9	45.4	0	NaN	12.6	21.3	0	NaN	4071.9	4320.9
	11172010	16.6	37.9	0.3	1.4	26.0	52.7	0	NaN	11.9	20.8	0	NaN	3996.1	4225.5
	12032010	21.7	56.9	1.9	4.1	30.6	63.8	0	NaN	14.4	31.5	2.6	1.4	4126.0	4245.3
	12172010	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 27. Overall Mean and Maximum Safety Experiences along San Diego to Guam Routes

Although routes for most of the origin-destination pairs and departure dates are within the thresholds, there are some origin-destination pairs and departure dates with results that exceed the safety thresholds. Tables 19–21 shows exceedances experienced by all environmental conditions, absolute winds, relative winds and seas. For the most part, the exceedances were mild, five knots or less for winds and one foot or less for seas.

Tables 22–24 show results within the safety thresholds. There were no exceedances of any of the environmental conditions. Tables 21, 22 and 27 have departure dates that are annotated by double asterisks (**). The results that were

generated for these departure dates were incomplete and removed from the table. The incompleteness of results is to be expected because these departure dates lacked results in the tables in the sensitivity section. Table 14 shows the lack of data that is seen in Table 23. Tables 16–18 show the lack of data that is seen in Table 24 and Table 27.

For some routes and environments, STARS output produced errors in wind speeds. These errors can be seen in the results that were generated for seven departure dates in Tables 26 and one departure date in Table 27. Data for these routes and environments have been excluded for the respective departure dates and are annotated by triple asterisks (***). With the data errors removed, the remaining data show moderate exceedances in winds, less than 10 knots of winds, and extreme exceedances in sea state, up to 10 feet.

From mild to extreme exceedances, the routes proved to be mostly robust when acted upon by environmental conditions. As to be expected, exceedances occurred more frequently in the late fall and early winter months. The extreme exceedances of nearly 10 feet occurred in the month of December. The time of year and the weather that occurs during that time do have effects on ship routes.

In summary, the rare and mild exceedances of safety thresholds indicate that routes are robust to uncertainty, as represented by an ensemble forecast.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. CONCLUSIONS

A. SUMMARY

This thesis set out to answer questions regarding the sensitivity and robustness of ship routes to environmental conditions and how important it is to take into consideration environmental uncertainty when determining a robust ship route. The sensitivity of the optimized routes showed that there were few routes that differed greatly in distance varying environmental forecasted conditions. The robustness of the optimized routes showed that the routes were safe under various environmental conditions. The time of year, with respect to seasons, is a major factor in the uncertainty of environmental conditions. The time of year and the forecasted weather conditions should definitely be taken into consideration when trying to determine an optimal ship route.

Given that weather is a variable that cannot be controlled, it is important to understand how that uncertainty can affect a ship route. The optimized routes that were generated by STARS showed little sensitivity and were robust to the environmental conditions. Although the environmental conditions proved to have an impact on the optimized routes, the generated routes were, for the most part, safe. However, because forecasted weather is not a guarantee but an estimate of a possible occurrence, ship routes based on forecasted environmental conditions are subject to change with the changing conditions. The optimized routes can be used as a basis, but it should be clear that even an optimized route may need to be altered to maintain robustness.

B. FUTURE WORK RECOMMENDATIONS

With more time, a thesis that covers an entire calendar year will guarantee all seasons and all possible environmental conditions. Within the year of research, careful documentation of actual weather conditions will provide a reference for the generated routes. In addition to expanding the length of time, the use of an additional ship type could show if the routes acted the same on different types of ships of different tonnage and different fuel sources.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. SAMPLE OF STARS INPUT FILE

```

REQUEST ID = $REQUESTID
CLASSIFICATION = UNCLASSIFIED
CAVEAT = NONE
REQUEST TYPE = $REQUESTTYPE
DESCRIPTION = San Diego CA to Guam
PASSAGE = San Diego CA to Guam
SHIP NAME = EFAS
SHIP CLASS = DD963.DAT
SHIP FOR DRAFT = 11.7
SHIP AFT DRAFT = 12.0
SHIP TRANSV GM = 2.6
MAX HEAD SEA = 25.0
MAX BEAM SEA = 25.0
MAX FOLLOW SEA = 25.0
MAX TRUE WIND = 35.0
MAX REL WIND = 65.0
MAX SPEED = 25.0
MIN SPEED = 18.0
MIN DIST 35 = 60
MIN DIST 50 = 120
DEPARTURE DATE = $DEPARTUREDATE
DEPARTURE TIME = $DEPARTURETIME
ARRIVAL DATE = $ARRIVALDATE
ARRIVAL TIME = $ARRIVALTIME
WIND MODEL = NOGAPS
WAVE MODEL = WW3_GLOBAL
CURRENT MODEL = NCOM_GLOBAL
UPPER BOUND WAYPOINTS = 4
UB NUMBER = 01
UB LATITUDE = 32.655575
UB LONGITUDE = -117.237769
UB NAV TYPE = GC
UB NUMBER = 02
UB LATITUDE = 51.224481
UB LONGITUDE = -150.712078
UB NAV TYPE = GC
UB NUMBER = 03
UB LATITUDE = 45.918669
UB LONGITUDE = 158.866392
UB NAV TYPE = GC
UB NUMBER = 04
UB LATITUDE = 13.442458
UB LONGITUDE = 144.665872
UB NAV TYPE = GC
LOWER BOUND WAYPOINTS = 4
LB NUMBER = 01
LB LATITUDE = 32.655575
LB LONGITUDE = -117.237769
LB NAV TYPE = GC
LB NUMBER = 02
LB LATITUDE = 5.723406
LB LONGITUDE = -135.341061
LB NAV TYPE = GC
LB NUMBER = 03
LB LATITUDE = 1.097358
LB LONGITUDE = 161.473958
LB NAV TYPE = GC
LB NUMBER = 04
LB LATITUDE = 13.442458
LB LONGITUDE = 144.665872
LB NAV TYPE = GC
END

```

Ship
Data

Environmental Data

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. SAMPLE OF STARS EXECUTIBLE FILE

```
#!/bin/bash

STARSDRIVER=/ITRI_AOTSR/otsr/stars_driver.2
COLLECTRESULTS=/ITRI_AOTSR/otsr/zipSTARSKmlHtmlResults

$STARSDRIVER \
  Route SanDiego2Guam \
  DepartureDate 20100603 \
  ArrivalDate 20101231 \
  RoutexEnvironment "A2 B2 C2 D2 E2 F2 Q1 R1 S1 T1 U1 V1 W1 X1 Y1 Z1 analysis" \
  \
  WeaxEnvironment "A2 B2 C2 D2 E2 F2 Q1 R1 S1 T1 U1 V1 W1 X1 Y1 Z1 analysis" \
  OnCompletionNotify slhall@nps.edu
$COLLECTRESULTS \
  Route SanDiego2Guam \
  DepartureDate 20100603

exit
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. SAMPLE OF STARS HYPERTEXT MARKUP LANGUAGE OUTPUT FILE

routex.20100601.NorfolkRota.A2

REQUEST ID = EFAS_20100601

REQUEST TYPE = ROUTEX

DESCRIPTION = Naval Station Norfolk to US Naval Station Rota Spain

PASSAGE = Naval Station Norfolk to US Naval Station Rota Spain

SHIP NAME = EFAS

DEPARTURE DATE = 06/01/2010

DEPARTURE TIME = 12:00:00

Point	Dtg	Lat	Lon	Ship Speed	Ship Course	Wind Speed	Wind Direction	SigWave Height	Sea Height	Sea Period	Sea Direction	Swell Height	Swell Period	Swell Direction	Current Speed	Current Direction	Horse Power	Distance
1	201006011200	36.944	-76.339	25.00	91.03	17.07	217.13	2.76	1.18	4.28	201.00	2.49	3.37	200.00	0.00	0.00	25.11	35.26
2	201006011324	36.931	-75.604	18.28	131.01	17.07	217.13	2.76	1.18	4.28	201.00	2.49	3.37	200.00	0.43	63.43	19.63	54.26
3	201006011622	36.334	-74.757	19.24	56.39	19.22	208.38	4.68	3.87	4.97	202.00	2.62	4.07	196.00	0.61	18.43	11.54	31.20
4	201006011800	36.621	-74.217	19.24	56.71	20.49	213.39	6.01	5.12	5.34	210.00	3.15	4.56	212.00	0.19	90.00	2.91	7.16
5	201006011822	36.686	-74.093	19.45	136.71	20.49	213.39	6.01	5.12	5.34	210.00	3.15	4.56	212.00	0.19	90.00	27.28	61.47
6	201006012131	35.938	-73.225	18.78	59.53	19.17	210.47	5.57	4.33	5.12	214.00	3.51	4.96	220.00	2.75	45.00	9.17	37.73
7	201006012332	36.254	-72.553	18.83	53.32	19.17	210.47	5.57	4.33	5.12	214.00	3.51	4.96	220.00	2.92	53.13	2.06	8.64
8	201006020000	36.340	-72.410	18.83	53.40	19.64	211.64	5.60	4.46	5.18	219.00	3.38	4.88	230.00	2.92	53.13	7.41	31.08
9	201006020139	36.648	-71.892	20.21	43.99	20.68	220.43	6.66	5.41	5.46	223.00	3.87	5.39	231.00	2.44	61.39	13.91	44.22
10	201006020350	37.177	-71.249	18.74	44.93	20.50	227.69	7.35	5.58	5.57	227.00	4.79	6.02	240.00	2.15	84.81	12.05	40.50

11	201006020600	37.653	-70.647	18.74	45.31	21.27	233.55	8.40	5.77	5.53	230.00	6.10	6.70	237.00	2.17	100.30	1.03	3.17
12	201006020610	37.690	-70.600	19.61	34.25	21.27	233.55	8.40	5.77	5.53	230.00	6.10	6.70	237.00	2.17	100.30	17.95	51.93
13	201006020849	38.404	-69.978	25.00	81.90	20.34	231.60	8.40	5.28	5.47	230.00	6.53	6.70	242.00	0.19	270.00	25.88	34.55
14	201006021011	38.483	-69.250	25.00	81.79	19.09	234.53	8.09	4.07	5.02	232.00	6.99	6.69	245.00	0.78	0.00	23.22	34.57
15	201006021134	38.563	-68.520	25.00	65.99	14.84	248.48	8.15	2.56	4.55	246.00	7.74	6.62	239.00	0.58	0.00	7.18	10.45
16	201006021200	38.633	-68.317	25.00	66.12	15.95	247.81	8.37	2.92	4.61	245.00	7.84	6.74	244.00	0.58	0.00	17.69	25.69
17	201006021301	38.806	-67.814	25.00	81.94	15.95	247.81	8.37	2.92	4.61	245.00	7.84	6.74	244.00	0.19	0.00	24.91	34.55
18	201006021424	38.884	-67.082	25.00	81.85	17.62	247.96	8.64	3.77	4.94	245.00	7.78	6.85	249.00	0.27	225.00	26.33	34.56
19	201006021547	38.964	-66.349	18.88	118.40	16.78	243.14	8.32	3.22	4.75	241.00	7.68	6.78	250.00	0.87	243.43	16.87	41.68
20	201006021800	38.631	-65.566	18.88	118.88	16.78	243.14	8.32	3.22	4.75	241.00	7.68	6.78	250.00	0.78	0.00	0.16	0.43
21	201006021801	38.627	-65.558	25.00	81.57	16.78	243.14	8.32	3.22	4.75	241.00	7.68	6.78	250.00	0.78	0.00	23.23	34.70
22	201006021924	38.710	-64.825	25.00	67.18	17.82	243.43	8.64	3.84	4.92	243.00	7.74	6.95	254.00	1.13	30.96	23.28	36.24
23	201006022051	38.942	-64.109	25.00	81.64	20.11	249.64	9.16	4.89	5.32	248.00	7.74	7.14	259.00	0.80	104.04	26.08	34.70
24	201006022214	39.024	-63.373	25.00	81.62	21.50	255.34	9.30	5.05	5.37	253.00	7.81	7.36	261.00	1.17	0.00	22.27	34.72
25	201006022338	39.106	-62.635	18.39	118.46	21.50	255.34	9.30	5.05	5.37	253.00	7.81	7.36	261.00	0.87	333.43	2.23	6.67
26	201006030000	39.052	-62.509	18.39	118.54	21.50	255.34	9.30	5.05	5.37	253.00	7.81	7.36	261.00	0.87	333.43	11.71	35.08
27	201006030154	38.771	-61.850	18.69	123.13	20.13	254.89	9.93	5.02	5.35	254.00	8.56	7.50	266.00	0.58	0.00	16.60	44.34
28	201006030416	38.365	-61.061	25.00	76.44	20.11	246.66	9.17	4.76	5.29	247.00	7.84	7.60	277.00	0.61	198.43	17.18	21.26
29	201006030507	38.447	-60.621	25.00	100.34	20.11	246.66	9.17	4.76	5.29	247.00	7.84	7.60	277.00	0.39	0.00	15.40	21.74
30	201006030600	38.381	-60.167	25.00	100.62	19.93	249.44	9.32	4.66	5.27	249.00	8.07	7.77	283.00	0.80	14.04	10.21	15.06
31	201006030636	38.335	-59.852	18.20	52.64	19.93	249.44	9.32	4.66	5.27	249.00	8.07	7.77	283.00	0.80	14.04	15.14	44.15
32	201006030901	38.779	-59.102	25.00	80.54	15.61	251.11	8.95	2.82	4.62	249.00	8.50	7.53	276.00	0.99	101.31	27.09	36.33
33	201006031028	38.876	-58.335	18.44	48.24	16.08	255.29	9.05	2.92	4.65	253.00	8.56	7.67	281.00	1.05	111.80	10.49	28.00
34	201006031200	39.186	-57.886	18.44	48.53	16.08	255.29	9.05	2.92	4.65	253.00	8.56	7.67	281.00	0.97	126.87	7.34	18.70
35	201006031300	39.391	-57.583	25.00	87.33	16.08	255.29	9.05	2.92	4.65	253.00	8.56	7.67	281.00	0.87	63.43	25.32	36.02
36	201006031427	39.417	-56.807	18.15	48.16	16.64	255.80	9.18	2.95	4.66	253.00	8.69	7.73	285.00	0.97	36.87	15.29	46.66
37	201006031701	39.933	-56.051	18.21	48.20	13.16	257.20	8.63	1.31	4.14	253.00	8.53	7.70	291.00	1.23	71.57	5.69	17.74
38	201006031800	40.130	-55.763	18.21	48.39	13.16	257.20	8.63	1.31	4.14	253.00	8.53	7.70	291.00	1.23	71.57	9.20	28.68
39	201006031934	40.446	-55.294	18.65	122.16	12.73	262.98	8.93	1.15	4.14	261.00	8.86	7.67	294.00	0.61	18.43	15.88	43.76
40	201006032155	40.055	-54.487	18.39	48.19	13.77	256.94	8.39	1.61	4.31	253.00	8.23	7.63	298.00	0.97	36.87	12.80	38.23
41	201006040000	40.479	-53.862	18.39	48.60	13.77	256.94	8.39	1.61	4.31	253.00	8.23	7.63	298.00	0.97	53.13	2.83	8.44

42	201006040027	40.571	-53.724	25.00	87.33	8.44	255.32	8.17	0.00			8.17	7.69	303.00	0.97	90.00	26.53	36.11
43	201006040154	40.597	-52.932	18.49	48.14	7.97	271.40	8.33	0.00			8.33	7.60	299.00	1.30	116.57	17.51	46.66
44	201006040425	41.113	-52.163	18.48	48.19	13.24	240.05	7.47	1.12	4.14	238.00	7.38	7.43	295.00	0.43	153.43	11.69	29.08
45	201006040600	41.435	-51.681	18.48	48.51	13.24	240.05	7.47	1.12	4.14	238.00	7.38	7.43	295.00	0.27	135.00	6.80	17.34
46	201006040656	41.626	-51.392	18.54	78.40	7.57	240.80	7.28	0.00			7.28	7.36	287.00	0.27	135.00	27.80	71.30
47	201006041047	41.855	-49.829	25.00	89.36	7.65	297.22	6.56	0.00			6.56	7.25	284.00	0.70	56.31	20.78	30.39
48	201006041200	41.858	-49.149	25.00	89.81	7.89	279.93	6.96	0.00			6.96	7.39	290.00	0.99	101.31	5.60	7.56
49	201006041218	41.859	-48.980	18.07	54.28	7.89	279.93	6.96	0.00			6.96	7.39	290.00	0.99	101.31	15.96	47.28
50	201006041455	42.316	-48.114	25.00	89.12	8.56	268.70	7.22	0.00			7.22	7.42	289.00	0.61	341.57	25.47	37.80
51	201006041625	42.322	-47.262	18.40	123.74	10.47	291.80	6.56	0.00			6.56	7.30	287.00	0.97	0.00	9.14	28.87
52	201006041800	42.054	-46.724	18.40	124.10	10.47	291.80	6.56	0.00			6.56	7.30	287.00	0.58	0.00	5.31	15.83
53	201006041851	41.905	-46.430	18.32	54.45	12.56	278.00	6.71	0.82	4.13	277.00	6.66	7.34	285.00	0.58	0.00	16.30	47.60
54	201006042127	42.363	-45.557	18.21	123.78	11.51	322.55	6.05	0.33	3.91	322.00	6.04	7.15	287.00	1.30	26.57	14.03	44.44
55	201006042353	41.948	-44.729	25.00	89.44	13.20	313.81	6.25	1.02	4.11	306.00	6.17	7.14	285.00	0.61	341.57	1.68	2.53
56	201006050000	41.949	-44.672	25.00	89.48	13.20	313.81	6.25	1.02	4.11	306.00	6.17	7.14	285.00	0.61	341.57	23.51	35.40
57	201006050124	41.951	-43.879	25.00	86.05	14.35	305.63	6.47	1.48	4.31	300.00	6.30	7.16	283.00	1.36	0.00	22.90	38.10
58	201006050256	41.992	-43.027	18.29	124.19	15.21	296.57	6.68	1.94	4.47	289.00	6.40	7.25	282.00	0.39	270.00	15.43	44.39
59	201006050522	41.573	-42.209	18.59	54.67	15.40	307.30	6.53	2.33	4.57	301.00	6.10	7.12	288.00	0.19	270.00	4.58	11.76
60	201006050600	41.686	-41.994	18.59	54.81	15.40	307.30	6.53	2.33	4.57	301.00	6.10	7.12	288.00	0.19	270.00	14.24	36.59
61	201006050758	42.036	-41.323	18.06	124.23	16.71	303.14	6.76	2.62	4.67	296.00	6.23	7.21	288.00	1.17	270.00	13.76	44.13
62	201006051024	41.619	-40.510	18.19	57.16	13.75	316.15	6.62	1.80	4.33	314.00	6.36	6.98	298.00	0.39	0.00	9.97	28.88
63	201006051200	41.879	-39.967	18.19	57.53	15.01	311.33	6.90	2.33	4.53	310.00	6.50	7.08	298.00	0.55	225.00	7.33	18.17
64	201006051259	42.041	-39.623	18.92	55.00	15.01	311.33	6.90	2.33	4.53	310.00	6.50	7.08	298.00	0.19	0.00	18.92	48.40
65	201006051533	42.500	-38.727	25.00	89.25	13.86	304.14	7.24	1.90	4.32	304.00	6.99	7.04	309.00	0.58	0.00	25.53	37.75
66	201006051704	42.505	-37.873	25.00	89.29	15.27	301.46	7.50	2.56	4.59	301.00	7.05	7.20	308.00	0.58	0.00	15.82	23.33
67	201006051800	42.509	-37.346	25.00	89.64	15.87	300.96	7.65	2.89	4.68	301.00	7.09	7.36	307.00	0.61	161.57	11.36	14.42
68	201006051834	42.510	-37.020	25.00	86.30	15.87	300.96	7.65	2.89	4.68	301.00	7.09	7.36	307.00	0.61	108.43	28.41	37.98
69	201006052005	42.548	-36.163	18.68	57.12	15.87	300.96	7.73	2.85	4.68	300.00	7.18	7.50	307.00	0.70	56.31	16.98	47.40
70	201006052237	42.973	-35.256	18.96	55.81	15.65	296.57	7.61	2.59	4.61	297.00	7.15	7.37	307.00	0.78	90.00	9.94	25.92
71	201006060000	43.215	-34.766	18.96	56.15	15.65	296.57	7.61	2.59	4.61	297.00	7.15	7.37	307.00	1.13	120.96	9.11	22.31
72	201006060110	43.421	-34.340	25.00	88.73	16.01	294.39	7.69	2.66	4.64	295.00	7.22	7.46	307.00	0.61	108.43	28.11	37.48

73	201006060240	43.431	-33.480	25.00	88.76	15.93	293.75	7.80	2.69	4.65	294.00	7.32	7.55	306.00	0.55	45.00	26.13	37.48
74	201006060410	43.442	-32.620	25.00	87.17	16.72	293.29	7.67	2.85	4.68	295.00	7.12	7.35	305.00	0.39	0.00	26.23	37.62
75	201006060540	43.469	-31.757	25.00	88.75	16.90	293.03	7.74	3.12	4.82	294.00	7.09	7.44	305.00	0.43	26.57	5.59	8.02
76	201006060600	43.472	-31.573	25.00	88.88	16.90	293.03	7.74	3.12	4.82	294.00	7.09	7.44	305.00	0.55	45.00	20.52	29.46
77	201006060710	43.480	-30.897	25.00	88.79	16.64	292.67	7.79	3.08	4.82	294.00	7.15	7.53	304.00	0.55	45.00	26.11	37.47
78	201006060840	43.490	-30.036	19.44	136.98	16.61	290.56	7.79	2.85	4.69	293.00	7.25	7.57	302.00	0.39	0.00	19.52	48.75
79	201006061111	42.893	-29.280	25.00	89.24	14.99	279.71	7.62	2.33	4.54	284.00	7.25	7.29	300.00	0.61	18.43	13.83	20.39
80	201006061200	42.897	-28.816	25.00	89.56	14.99	279.71	7.62	2.33	4.54	284.00	7.25	7.29	300.00	0.00	0.00	12.60	17.24
81	201006061241	42.898	-28.424	19.13	136.39	14.71	277.59	7.58	2.33	4.56	280.00	7.22	7.35	299.00	0.27	225.00	19.40	48.14
82	201006061512	42.315	-27.675	25.00	89.71	16.24	286.70	7.03	2.53	4.62	287.00	6.56	7.40	302.00	0.27	45.00	26.75	37.77
83	201006061643	42.315	-26.824	19.51	139.15	16.55	285.67	7.05	2.66	4.70	286.00	6.53	7.49	301.00	0.00	0.00	10.46	25.03
84	201006061800	41.999	-26.457	19.51	139.40	16.97	283.24	7.07	2.85	4.82	285.00	6.46	7.59	300.00	0.39	0.00	9.99	24.89
85	201006061916	41.683	-26.095	25.00	103.52	16.97	283.24	7.07	2.85	4.82	285.00	6.46	7.59	300.00	0.58	0.00	25.33	37.75
86	201006062047	41.533	-25.278	19.60	139.43	16.85	281.31	7.04	2.79	4.80	281.00	6.46	7.65	298.00	0.58	0.00	19.84	49.94
87	201006062320	40.899	-24.562	25.00	110.27	14.53	294.51	6.47	1.84	4.37	293.00	6.20	7.34	301.00	0.19	90.00	12.02	16.63
88	201006070000	40.802	-24.218	25.00	110.49	14.70	294.19	6.50	1.94	4.45	295.00	6.20	7.48	299.00	0.19	90.00	15.83	21.91
89	201006070052	40.673	-23.767	18.12	134.59	14.70	294.19	6.50	1.94	4.45	295.00	6.20	7.48	299.00	0.19	90.00	16.80	46.55
90	201006070326	40.127	-23.045	25.00	112.14	17.35	192.95	5.65	2.53	4.51	209.00	5.05	7.40	263.00	0.19	0.00	24.62	34.62
91	201006070449	39.907	-22.348	18.31	130.90	13.81	193.84	5.20	1.35	4.16	205.00	5.02	7.78	269.00	0.19	0.00	7.59	21.41
92	201006070600	39.673	-21.998	18.31	131.12	13.81	193.84	5.20	1.35	4.16	205.00	5.02	7.78	269.00	0.19	270.00	11.32	31.82
93	201006070744	39.323	-21.481	18.03	135.31	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	270.00	15.77	48.10
94	201006071024	38.751	-20.758	18.66	138.39	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.79	29.75
95	201006071200	38.379	-20.338	18.66	138.65	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	315.00	6.95	20.10
96	201006071304	38.127	-20.057	18.15	66.78	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.19	41.66
97	201006071522	38.398	-19.243	18.27	67.26	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	315.00	14.20	41.82
98	201006071739	38.665	-18.419	18.26	67.84	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	270.00	2.16	6.17
99	201006071800	38.704	-18.297	18.26	67.91	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	270.00	12.54	35.85
100	201006071957	38.926	-17.586	18.27	139.40	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	16.35	48.31
101	201006072236	38.313	-16.918	25.00	104.25	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	225.00	24.76	34.84
102	201006080000	38.168	-16.202	25.00	104.71	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	1.06	1.55
103	201006080003	38.161	-16.170	25.00	104.14	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	24.65	36.19

104	201006080130	38.012	-15.428	25.00	104.00	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	24.49	35.95
105	201006080256	37.864	-14.692	18.31	143.69	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	225.00	16.13	46.75
106	201006080530	37.235	-14.112	25.00	103.81	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.70	12.47
107	201006080600	37.185	-13.859	25.00	103.96	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.50	22.20
108	201006080653	37.095	-13.409	25.00	103.55	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	23.20	34.05
109	201006080815	36.960	-12.718	25.00	103.20	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	270.00	23.07	33.24
110	201006080934	36.832	-12.044	25.00	102.69	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.44	32.15
111	201006081051	36.712	-11.392	25.00	101.92	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.79	28.35
112	201006081200	36.613	-10.816	25.00	102.26	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.59	2.27
113	201006081205	36.605	-10.770	25.00	100.63	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.84	28.42
114	201006081313	36.516	-10.191	19.50	66.81	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.41	43.51
115	201006081527	36.799	-9.358	19.44	68.58	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	225.00	18.48	44.64
116	201006081745	37.068	-8.490	25.00	137.76	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	116.57	4.49	6.09
117	201006081800	36.992	-8.405	25.00	137.82	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	116.57	4.75	6.45
118	201006081815	36.913	-8.314	20.27	100.06	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	116.57	44.24	97.33
119	201006082303	36.613	-6.324	0.00	0.00	0.00	270.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	153.43	0.00	0.00

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

- Brown, G. G., Kline, J. E., Rosenthal, R. E., & Washburn, A. R. (2007). Steaming on convex hulls. *Interface*, 37, 342–352.
- Department of the Navy Office of the Chief of Naval Operations. (2007). *Sustainment at sea NWP 4-01.2*. Washington, DC: Department of the Navy.
- Dolinskaya, I. S., Kotinis, M., Parsons, M. G., & Smith, R. L. (2009). Optimal short-range routing of vessels in a seaway. *Journal of Ship Research*, 53, 121–129.
- Google Earth. (2010). Google Earth (Version 5.2) [Software]. Available from <http://www.google.earth/index.html>
- Google Earth. (2011). Google Earth (Version 6.2) [Software]. Available from <http://www.google.earth/index.html>
- Hogan, T. F., Rosmond, T.E., & Gelero, R. (1991). The NOGAPS forecast model: a technical description. *Naval Oceanographic and Atmospheric Research Laboratory*, 13, i.
- Lynch, P. (2008). The origins of computer weather prediction and climate modeling. *Journal of Computational Physics*, 227, 3431–3444.
- McLay, J., Bishop, C. H., & Reynolds, C. A. (2010). A local formulation of the ensemble transform (ET) analysis perturbation scheme. *Weather and Forecasting*, 25, 985–993.
- Montes, A. A. (2005). *Network shortest path application for optimum track ship routing* (Master's thesis, Naval Postgraduate School). Retrieved from <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA435601>
- Naval Historical Center. (2001). Typhoons and hurricanes: pacific typhoon, 18 December 1944. Retrieved from <http://www.history.navy.mil/faqs/faq102-4.htm>
- Naval Historical Center. (2005). U.S. Navy ships lost in selected storm/weather related incidents. Retrieved from <http://www.history.navy.mil/faqs/faq102-2.htm>
- National Weather Service, Ocean Prediction Center. (2009). NCOM MODEL. Retrieved from <http://www.opc.ncep.noaa.gov/OceanFcsts/NCOMinfo.shtml>
- Sivillo, J. K., Ahlquist, J. E., & Toth, Z. (1997). An ensemble forecasting primer. *Weather and Forecasting*, 12, 809–818.

Stoughton, S. (2010). *A Process for applying forecast uncertainty in planning for underway evolutions along intended track* (Master's thesis, Naval Postgraduate School). Retrieved from http://edocs.nps.edu/npspubs/scholarly/theses/2010/Sep/10Sep_Stoughton.pdf

Vlachos, D. S. (2004). Optimal ship routing based on wind and wave forecasts. *Applied Numerical Analysis and Computational Mathematics*, 1, 547–551.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California
3. Associate Professor Eva Regnier
Naval Postgraduate School
Monterey, California
4. Dr. Jim Hansen
Naval Research Laboratory
Monterey, California
5. Research Assistant Professor Dashi Singham
Naval Postgraduate School
Monterey, California
6. LT Stacey L. Hall, USN
Meridian, Mississippi